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MODIFYING PENAEID-TRAWL SPREADING MECHANISMS TO IMPROVE ENVIRONMENTAL EFFICIENCY

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Abstract

The environmental efficiency of demersal trawls can be defined within measures of three response variables: (i) species selectivity; (ii) extent and intensity of habitat impacts; and (iii) energy efficiency. All three variables affect all fisheries, but especially those targeting penaeid prawns (or shrimp).

Penaeid-trawl fisheries are globally distributed in tropical and temperate latitudes and involve vessels (~8−25 m) towing small-meshed, single- or multi- funnel-shaped nets on the seabed, horizontally spread by hydrovanes (called 'otter boards'), and less commonly, rigid beams. To date, most of the efforts towards improving the environmental efficiency of penaeid trawls have concentrated on gear selectivity specifically, via bycatch reduction devices (BRDs) in the codend (to address i above). Although somewhat effective (30–70% reductions), BRDs offer few perceived benefits to fishers and, in many fisheries, there is resistance to their adoption.

It is known that the anterior trawl section affects all three response variables above, which might concomitantly be mitigated through modifications that could potentially provide fishers with a realised benefit—increased energy efficiency (and therefore greater adoption). A primary objective of this thesis was to investigate the potential for holistically improving penaeid-trawl environmental efficiency through research focussed on the anterior section of the gear; specifically the spreading mechanisms (otter boards, sleds, beams and sweeps).

The treatments tested comprised three broad categories: (i) revising otter boards and their rigging; (ii) substituting otter boards with a beam; and then (iii) amalgamating key concepts across both methods. Modifications within the first category included removing sweeps and testing a novel otter board (i.e. the batwing). Within the second category, beams were modified in attempts to maintain target catches while minimising bycatch, habitat contact and energy intensity. The third group of modifications involved exploiting the concepts underlying an identified inherently superior species selection of beam trawls to otter trawls via counter-herding devices, termed 'simple anterior fish excluders'—SAFEs.

Where appropriate, the treatments were compared against controls for their utility in mitigating the three response variables. The overall results demonstrated that selectivity can be improved (i.e. bycatch reduction) by using a beam trawl, SAFE or by removing sweeps; habitat impacts will be reduced when using batwings; and, while overall energy intensity was not improved, an important component—drag—can be alleviated using a beam trawl or batwing otter boards. For targeted

catches, the conventional otter trawls caught more total penaeids, but the beam trawls had comparable penaeid catches when corrected for fuel-to-catch ratios.

A key conclusion from the thesis is that no single treatment will be effective for significantly improving all three response variables; however, anterior modifications lowering drag (the beam trawl and batwing otter boards) provide fishers with the greatest potential benefit—lower fuel usage. Ultimately, because otter trawls are the most ubiquitous demersal trawls, the batwing otter boards were perceived to have the greatest potential with their greater fuel efficiency and lower habitat impacts. Additionally, applying counter-herding devices (i.e. a SAFE) to otter trawls could provide a cost-effective modification that will reduce bycatch without affecting targeted penaeids, when trawl spread ratios (defined as the wing-end spread ÷ headline length) are maintained.

It is likely that one of the greatest benefits from spreading-mechanism modifications will be lower unaccounted mortality to bycatch species, by limiting the potential for injury sustained from escape attempts (i.e. through the mesh and/or BRDs), which may occur when individuals enter the trawl. The overall results on improving spreading-mechanism environmental efficiency will complement future work with other anterior-trawl sections—frame lines, ground gear and the body—for a more holistic approach to improving overall efficiency

Overall, this thesis provides a comprehensive assessment of penaeid-trawl spreading-mechanism modifications and gear alternatives for improving penaeid-trawl environmental efficiency. The findings are not only applicable to Australian penaeid (and non-penaeid) trawl fisheries, but also similar fisheries overseas.

Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly authored works that I have included in my thesis.

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McHugh, M. J., Broadhurst, M. K., Sterling, D. J. and Millar, R. B. (2015) A 'simple anterior fish excluder' (SAFE) for mitigating penaeid-trawl bycatch. *PloS One* **10**(4): e0123124.

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Author Matt K. Broadhurst	Designed experiments (19%) Wrote and edited paper (18%) Statistical analysis (25%)
Author David J. Sterling	Designed experiments (12%) Wrote and edited paper (10%)
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List of Abbreviations used in the thesis

Abbreviation	Meaning
AOA	Angle of attack
B	Bars
BRD	Bycatch reduction device
CL	Carapace length
cm	centimetre
E	East
FDR	False discovery rate
FRC	Footrope contact
g	gram
GPS	Global positioning system
h	hour
ha	hectare
Ho	null hypothesis
K	1000
kg	kilogram
kgf	kilogram of force
kw	kilowatt
L	litre
LM	Linear model
LMM	Linear mixed model
LRT	Likelihood ratio test
m	meter
mm	millimetre
min	minute
n	Number
N	Normal
NSW	New South Wales
NSW DPI	New South Wales Department of Primary Industries
p	p-value (the attained level of significance)
PA	Polyamide
PE	Polyethylene

PFA	Professional fishermen’s association
PP	Polypropylene
PU	Polyurethane
PVC	Polyvinyl chloride
s	Second (i.e. 1/60 minute)
S	South
SAFE	Simple anterior fish excluder
SE	Standard error
SMO	Stretched mesh opening
SOG	Speed over ground
STW	Speed through water
SR	Spread ratio
t	tonne
T	Transversals
TL	Total length
TSC	Total system contact
USA	United States of America
vs	Versus
$A	Australian Dollar
$^{-1}$	per (e.g. m^{-1}—per meter)
^{2}	square (e.g. m^2—square meter)
Ø	Diameter
%	percentage
~	Approximately
×	Times
÷	Divided by
±	Plus or minus
≤	Less than or equal to
<	Less than
>	Greater than
^{o}	Degree (e.g. 20^{o} =20 degrees)

Chapter 1 General introduction

This chapter has been integrated into a definitive review article submitted for publication: McHugh, M. J., Broadhurst, M. K. and Sterling, D. J. (In review) Reducing the global environmental impacts of penaeid trawls: a review and protocol forwards (Appendix 1).

Introduction

Mobile demersal fishing gears are used globally and are believed to have originated in 14th century England with the first records of the 'wondyrchoun'; a modified oyster dredge (Robinson, 1996). The wondyrchoun evolved into a 'beam trawl'—a funnel-shaped net held open by a wooden beam with skids/sleds attached at each end—that was used to target benthic fish and crustaceans (Figure 1. 1a). The beam trawl remained the only demersal trawl until the late 19th century when a new design (termed the 'otter trawl') was invented to target a larger diversity of fish (Cunningham, 1896; Robinson, 1996; Graham, 2006). Otter trawls retained the funnel-shaped net of beam trawls, but the rigid spreading mechanism was replaced by a pair of hydro-vanes ('otter boards') configured at angle of attack (AOA; typically 30–50^{o}) to hydrodynamically maintain the trawl opening (Figure 1. 1b).

Notwithstanding centuries of development (and ongoing beam trawl use), it was the otter trawls' introduction and the increase in steam-powered trawlers in the late 19th century that are regarded as the beginning of the fishing revolution (Garstang, 1900; von Brandt, 2005; Graham, 2006; Engelhard, 2009). Prior to the 1880s, the unreliability of sailing vessels for maintaining consistent speeds limited them to beam trawling across flat and relatively firm substrate and therefore targeting only associated species (e.g. flatfish and rays). Steam-powered trawling allowed fishers to use otter trawls with increased vertical (headline height) and lateral (wing-end spread) openings to explore more diverse habitats (e.g. further offshore) and to target different species (Cunningham, 1896; Winger *et al*., 2010; Engelhard, 2009).

Demersal beam and otter trawls currently account for ∼25% of the total global marine harvest (~80 million tons) and with catches from most taxonomic groups (excluding arachnoids, echinoderms, tunicates and most bivalves; Kelleher, 2005; Watson *et al*., 2006). While the importance of such gears to global harvests is clear, they also are among the most controversial; typically associated with some of the largest collateral mortalities evoked through discarding (Kelleher, 2005).

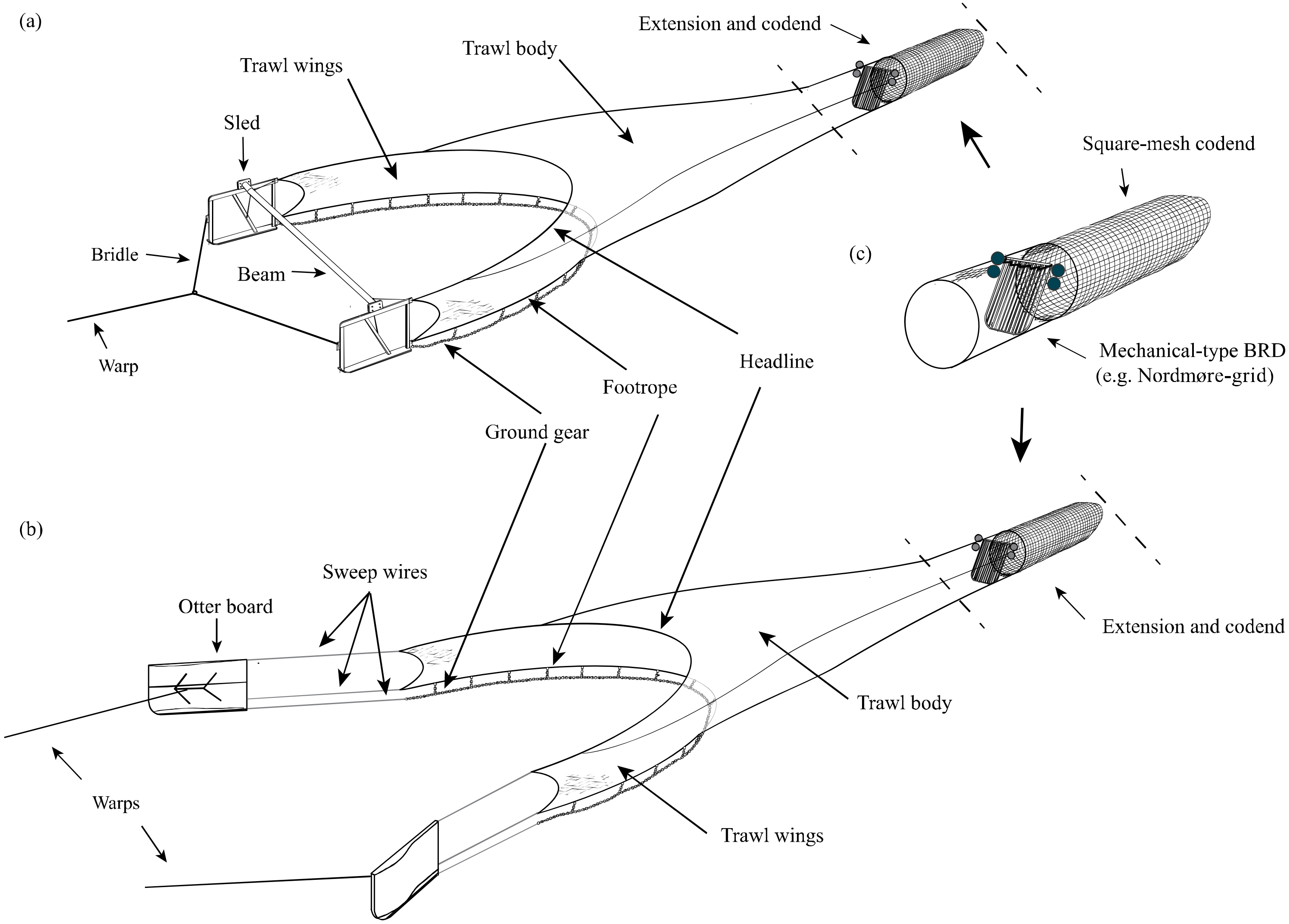

Figure 1. 1. A diagrammatic representation with key terminology of typical (a) beam- and (b) otter-trawl configurations, with a (c) mechanical-type bycatch reduction device (BRD) and a square-mesh codend.

Specifically, many otter trawls often are characterised by disproportional catches of unwanted organisms which comprise a diverse assemblage of non-target individuals, including juveniles of the targeted species (collectively termed ‘bycatch’; for reviews see Andrew and Pepperell, 1992; Alverson *et al.*, 1994; Kelleher, 2005). This is especially the case for penaeid trawls which, despite accounting for only 1.5% of the total global harvest above, contribute more than 27% of the annual weight of by-catch (most recently estimated at ~7.3 million tonnes by Kelleher, 2005).

Penaeid distributions and trawl configurations

Penaeid trawling dates back to the start of the 20th century in the USA (Captiva, 1966) and currently occurs throughout tropical and temperate latitudes, with some 110 species targeted across shallow (~2 m) coastal fringes and embayments to deeper (>50 m) offshore habitats. Penaeid trawlers typically range between ~8 and 25 m, and tow various trawl systems. In many cases, the application and/or legislation of particular designs in countries are based on either the preferential use of particular arrangements that were in place if and/or when fisheries legislation was established or, more recently, unsubstantiated perceptions about how legislated gear suited prevailing management priorities (Davies *et al.*, 2009).

Notwithstanding considerable diversity, most penaeid trawls are deployed within two general anterior configurations (Figure 1. 2). The traditional, albeit antiquated, penaeid trawling system involves a single trawl spread by either two otter boards or a beam (Figures 1. 1 and 1. 2). While some small inshore vessels tow single trawls, this method has been superseded in most industrial fisheries by multi-trawl configurations (Knake *et al.*, 1958; Bullis and Floyd, 1972; Sterling, 2005); among which ‘twin’ or ‘double’ rig is by far the most common, involving two trawls with independent otter boards or beam configurations and bridles and towed from outriggers on each side of the vessel (Knake *et al.*, 1958; Gillett, 2008; Figure 1. 2).

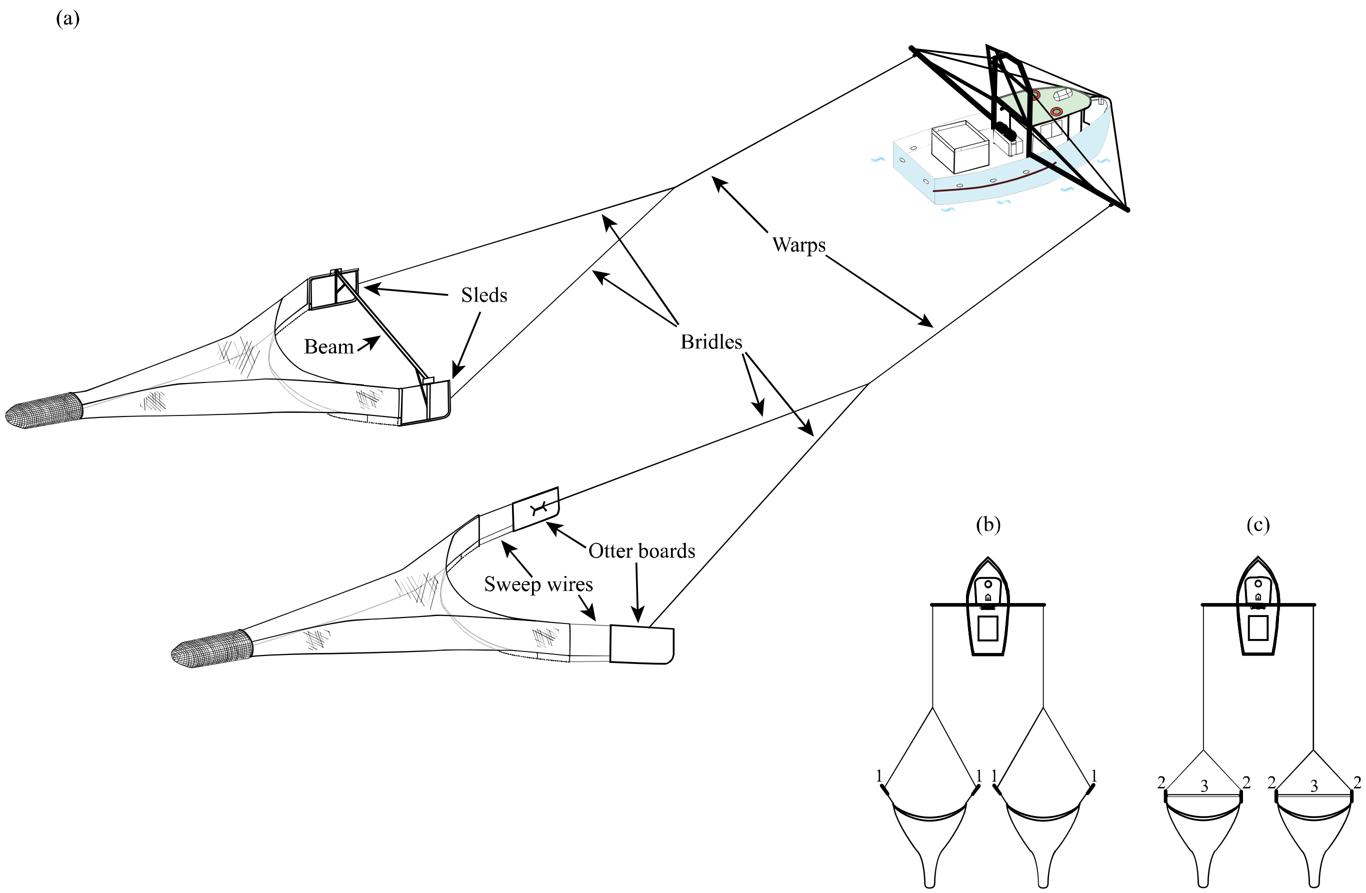

Figure 1. 2. (a) Three-dimensional view of a vessel towing double rig (with a single beam and otter trawl) from outriggers, and two-dimensional top views of (b) otter- and (c) beam-trawl configurations. Superscript numbers represent ^{1} otter boards, ^{2} sleds and ^{3} beams.

Penaeid species behaviour in relation to trawls

Irrespective of their spreading mechanism (beams or otter boards and sleds) or number of nets, like all mobile gears, penaeid trawls have evolved to maximise catches of the target species (Gillett, 2008). At a basal level, a trawl's capture efficiency depends on the stimuli (tactile and/or visual) from the different components eliciting a response from the target species, whereby they are encouraged into the net. While some penaeids do orientate above the seabed (e.g. during migration or reproduction), most predominantly reside within or very close to the substrate (Ruello, 1973; Coles, 1979; Wassenberg and Hill, 1994).

There are few studies describing penaeid reactions to towed gears, although similar to other crustaceans, and unlike fish, their behaviour appears quite specific, with responses mostly evoked by tactile stimuli (Coles, 1982; Newland and Chapman, 1989; Watson, 1989; Eayrs, 2002). Specifically, Watson (1989) observed that penaeid (mostly *Peneaus aztecus*, Ives) responses to an approaching trawl were limited to contraction of the abdomen after mostly tactile stimuli from contact with the trawl ground gear (Figure1.1). Depending on their orientation, such contraction effectively propelled penaeids varying distances (depending on their size; Daniel and Meyhofer, 1989). This initial escape response was repeated three to five times, after which the penaeids attempted to orientate to the sea bed and were quickly forced the against webbing panels, eventually tumbled down the net and into the codend (Watson, 1989).

By comparison, the reactions of fish (and some cephalopods) to trawls are somewhat more complex (Glass and Wardle, 1989; Winger *et al*., 2010). Fish initially detect trawls via a combination of visual and tactile stimuli generated by moving trawl-wires and associated gear (Main and Sangster, 1981); the rate of which is determined by various environmental (e.g. temperature, turbidity and salinity) and biological factors (e.g. size, perception and school density). Most individuals orientate away from these stimuli and, depending on their swimming ability and physiological responses, either avoid the gear altogether or are progressively herded back toward the trawl opening (Winger *et al*., 2010). Owing to compensatory movements in response to shifts in their visual field (termed the optomotor response) fish that enter the trawl attempt to maintain station in the 'current' (termed rheotaxis) generated as they are displaced past various components, which are perceived as stationary objects (see Wardle, 1989; Watson, 1989; Winger *et al*., 2010). After some period, depending on species-specific swimming abilities and especially size, fish invariably tire, often rise in the trawl (High and Lusz, 1966) and fall back towards the taper of the codend (Winger *et al*., 2010). At this point individual fish often become disorientated as crowding occurs, resulting in increased swimming speeds and random attempts at escape towards the sides of the trawl. Such movement can be promoted via the displacement of water anterior to the catch (Broadhurst, 2000); which effectively reduces the perceived current and allows fish to maintain a faster swimming speed for any given energy expenditure (Videler and He, 2010).

The broad behavioural differences described above are reflected in the key design differences between many fish and penaeid trawls. Specifically, schooling fish species are targeted with high vertical opening trawls, with a medium-to–low (0.3–0.5) so-called spread ratio (SR; defined as the wing-end spread ÷ headline length) and often long sweep wires (Figure 1.1) and varying mesh sizes that are progressively smaller throughout a long body to the codend (to herd and fatigue species).

In contrast, penaeid trawls have mostly low vertical openings with a high SR (0.5–0.8) and fairly steep side tapers—primarily because the horizontal opening and bottom contact of a penaeid trawl are more important than the length. Many penaeid trawls also have so called 'lead-a-head' on the top panel which is designed to exploit the initial behavioural response after contact with the footrope and prevent individuals jumping over the headline. Because of the random movements by penaeids in the anterior trawl, mesh sizes typically are small and uniform in size (30–50 mm stretched mesh opening–SMO; Vendeville, 1990).

Environmental inefficiency of penaeid trawls

The inherent design characteristics of penaeid trawls, including their small mesh, benthic contact and use across inshore areas synonymous with diverse assemblages of small species, explains their disproportionate unwanted bycatches (Andrew and Pepperell, 1992; Broadhurst, 2000; Broadhurst *et al.*, 2006). Historically, this poor size and species selectivity and the high associated collateral mortality has remained the most pressing issue facing the management of penaeid trawling globally (Davies *et al*., 2009). However there are two other broad, problematic issues associated with penaeid trawling.

A second more recent concern, and ancillary to the obvious implications that the mortality of large quantities of bycatch (and discarded catches) has on stocks and the subsequent cascading responses throughout the food web, is the unseen mechanical impacts of penaeid trawls on the seabed (Burridge *et al*., 2003). The key penaeid-trawl components (e.g. the 'spreading mechanisms' and ground gear; Figure 1. 1) need to be sufficiently heavy to maintain bottom contact and stimulate the upward movement of benthic-orientated penaeids to facilitate their capture. There is a concern that such contact may negatively affect sessile non-target organisms (epi- and infauna) across some sensitive habitats (Hutchings, 1990).

Third, there is a more recent but growing economic impetus for improved energy efficiencies; attributable to the rising cost of fossil fuels and awareness about the socio-economic impacts of climate change (Tyedmers *et al*., 2005). Globally, some crustacean trawl fisheries require over 10,000 litres of fuel per tonne landed, with some penaeid fisheries being the most fuel intensive (Parker and Tyedmers, 2014). In many fisheries, fuel costs alone contribute >50% towards production costs; a large component of which can be attributed to the spreading mechanisms (Funk *et al*., 1998; Thomas *et al*., 2010; Suuronen *et al*., 2012). It seems reasonable to postulate that the ongoing viability of penaeid trawling into the 21st century requires a coherent, multi-faceted technological approach towards solving the above three problematic issues.

Resolution attempts to date

Owing to the visual impacts of large quantities of discarded bycatch, the majority of research done-to-date has concentrated on addressing the first category above, and more specifically, mitigating unaccounted fishing mortalities through improved size and species selection and, to a lesser extent, changes to fishing operations (Broadhurst *et al*., 2006). A large percentage of the global effort in this mostly has involved modifying the posterior sections of trawls (i.e. the codend, extension and aft belly) to include physical bycatch reduction devices (BRDs; Figure 1. 1), which were most recently reviewed by Broadhurst (2000).

The first primary-literature studies describing BRDs in penaeid trawls date back to the early 1960s (Broadhurst, 2000). Many BRDs subsequently have been tested, but virtually all can be classified according to their principal design function of separating organisms via differences in either size or behaviour (Broadhurst, 2000). The first category (termed ‘mechanical-type’ BRDs) typically comprise a grid with an appropriate bar spacing, often located posterior to a guiding funnel/panel at an angle of <50^{o} in the trawl extension to direct organisms larger than penaeids through an escape exit. The second category (termed ‘behavioural-type’ BRDs) often have strategically positioned openings designed to promote the passive escape of swimming fish, including those smaller than penaeids. Such designs must either: (i) contain components (e.g. panels of mesh) that reduce relative current to a velocity (typically 0.2–0.5 m s^{-1}; Watson *et al*., 1993) where small fish are able to maintain position close to escape openings (Rogers *et al*., 1997) or (ii) be positioned in the trawl where there is a substantial reduction in relative water flow (i.e. immediately anterior to the codend; Broadhurst, 2000).

Many BRDs have improved the selectivity of penaeid trawls, but none are 100% effective, with total bycatch reductions nearly always <70% and mostly around 30−50% (Broadhurst, 2000).

Also in many fishers, there has been resistance to adopt what are considered an additional burden to operations (i.e. no perceived benefits to fishers).

More recently, for some fisheries, mortalities to the remaining discards have been further mitigated via changes to on board handling practices. However, a suite of environmental, technical and biological factors restrict the utility of such changes (in terms of actually reducing discard mortality) to inshore and estuarine, small-scale operations (Broadhurst *et al*., 2006).

Much less research has been done to mitigate the remaining two broad (but inter-related) sustainability concerns associated with penaeid trawling, and especially habitat impacts. The impacts associated with demersal trawling have been extensively studied for their short and long term effects on a variety of habitats (De Groot, 1984; Hutchings, 1990; Jones, 1992). Globally, recurring impacts from demersal trawls potentially have detrimental consequences for ecosystem function and its ability to tolerate disturbance without collapsing (Thrush and Dayton, 2002). While penaeid fisheries typically involve relatively small gears compared to the large configurations employed in some demersal fisheries (e.g. spreading mechanisms in excess of 1 t, and numerous chains on beam trawls, etc.) they can still potentially inflict major damage to various habitats (e.g. Hutchings, 1990) especially where repeated trawling occurs (Collie *et al*., 1997; Drabsch *et al*., 2001; Pitcher *et al*., 2009).

Notwithstanding the potential for all trawl components to impact the substrate, otter boards inflict the most damage per unit area of seabed (although the sweep wires and ground gear impact a larger area; Gilkinson *et al*., 1998; Eigaard *et al*., 2015). While reducing the trawl-gear components' weight and/or contact on the substrate could potentially limit demersal trawl impacts, is often not possible because the weight helps maintain the gear in an operational position on the substrate (Valdemarsen and Suuronen, 2003; Ivanović *et al*., 2011). Additionally, the spreading-mechanism contact (via substrate disturbance) can potentially influence catches (e.g. Broadhurst *et al*., 2012; 2015a).

The energy (i.e. fuel intensity) required to operate a trawl is also greatly influenced by the weight, substrate contact and hydrodynamic drag; especially from the spreading mechanisms (Suuronen *et al*., 2012). While simple changes to the spreading mechanisms (e.g. reducing their weight, substrate contact and hydrodynamic drag) will potentially alleviate the high energy intensity of many trawl configurations, there are very few examples being applied in penaeid fisheries.

Considering that the anterior trawl section, and especially the spreading mechanisms, affects all three environmental inefficiency issues associated with penaeid trawling, it seems reasonable to assume that their modification could provide holistic solutions. Within this context there is the potential to give fishers a realised benefit—increased energy efficiency (and therefore potentially greater adoption of modified, environmentally friendly gears).

Thesis objectives

Considering the above, my primary objective in this thesis was to investigate the potential for holistically improving penaeid-trawl environmental efficiency (measured as reductions in bycatch, habitat impacts and energy inefficiencies) through research focused on the spreading mechanisms (otter boards, sleds, beams and sweeps) and by exploiting known and hypothesised trawl-engineering characteristics and species-specific behavioural differences. The specific aims were to assess treatments from three broad categories: (i) substituting otter boards with beams, (ii) amalgamating positive environmental concepts across both methods; and then within otter trawls (iii) revising otter boards and their rigging.

Modifications within the first category above involved configuring beams in attempts to maintain target catches while addressing all three environmental issues. The second group of modifications involved exploiting the concepts underlying an identified, inherently superior species selection of beam trawls to otter trawls via new and novel counter-herding devices, which I termed 'simple anterior fish excluders'—SAFEs. The SAFEs were designed to reduce bycatch, but with future scope to also reduce drag. For the third category, I assessed the utility of removing sweeps and comparing several otter boards including a new novel design (termed the 'batwing') to reduce habitat impacts and energy usage.

The four data chapters of this thesis sequentially address the above aims:

Chapter 2: Comparing and modifying penaeid beam- and otter-trawls to improve ecological efficiencies (categories i–iii above);

Chapter 3: A 'simple anterior fish excluder' (SAFE) for mitigating penaeid-trawl bycatch (ii above);

Chapter 4: Comparing three conventional penaeid-trawl otter boards and the new batwing design (iii above); and

Chapter 5: Relative benthic disturbances of conventional and novel otter boards (iii above).

Chapters 2–5 are prepared as manuscripts that have been published, but because they are presented as stand-alone manuscripts there is some minor repetition of background literature and methods.

The final chapter (Chapter 6) provides a summary of the research outcomes and a general discussion of their implications, as well as limitations and future recommendations.

Justification for future work is further detailed in the review provided in Appendix 1. This review not only considers the thesis findings, but all other primary literature—from which a protocol is proposed for the holistic refinement of penaeid trawls to improve environmental efficiency.

Chapter 2: Comparing and modifying penaeid beam- and otter-trawls to improve ecological efficiencies.

Published in *Fisheries Management and Ecology* (McHugh, M. J., Broadhurst, M. K., Sterling, D. J. and Millar, R. B. (2014) Comparing and modifying penaeid beam- and otter-trawls to improve ecological efficiencies. *Fisheries Mangement and Ecology* **21**: 299–311.)—incorporated in Appendix 2.

Abstract

In an attempt to improve the selectivity and engineering performances of generic penaeid trawls, three established and one novel spreading-mechanism configuration were assessed: otter boards attached (i) with and (ii) without 3.15-m sweep wires to a 7.35-m headline trawl, and a beam rigged directly to a 9.19-m trawl (iii) with and (iv) without a horizontal wire and plastic streamers. Despite more surface area (7.5 vs 6.0 m^2) both beam-trawl configurations had significantly lower drag than the otter trawls (≤30%). When catches were standardised to ha^{-1}, the otter trawl with sweep wires retained significantly more (1.3 to 2.4 times) school prawns, *Metapenaeus macleayi* (Haswell), than the other three configurations. Within systems, removing sweep wires or adding a horizontal wire significantly reduced the unwanted catches of a key teleost (southern herring, *Herklotsichthys castelnaui*, Ogilby) by 41 and 48%. The results illustrate the utility of simple anterior modifications for independently addressing penaeid-trawling environmental issues.

Keywords: penaeids, bycatch reduction; modifications; otter trawls; beam trawls; drag

Introduction

Mobile demersal fishing gears, including beam and otter trawls, are among the most commonly used commercial methods; accounting for ~25% of the total global catch or ~15% of all marine fish and >80% of penaeid catches (Kelleher, 2005; Watson *et al.*, 2006). While their contribution towards global harvests is important, demersal trawls and especially those targeting penaeids often are associated with poor size and species selectivity (Kelleher, 2005) and indirect (e.g. predator removal) effects on epi- and in-fauna (Kaiser *et al.*, 2002). Such impacts cause varying levels of unaccounted fishing mortality, and can have negative consequences for key stocks and habitats (Broadhurst *et al.*, 2006). Demersal trawling also requires large amounts of fuel, often representing up to 30% of an operator's total costs (Thomas *et al.*, 2010).

Historical recognition of the above ecological and economic issues has led to the investigation of resolution strategies; mostly via isolated attempts at improving size and species selection using retrospectively-fitted bycatch reduction devices in penaeid (e.g. Broadhurst, 2000) and fish trawls (e.g. Jennings and Revill, 2007) and proposing alternatives that reduce benthic impacts (Kaiser *et al.*, 2002; Kennelly and Broadhurst, 2002). Recently, improved fuel efficiencies have been achieved through better vessel engineering (e.g. hull design or propulsion systems; Thomas *et al.*, 2010), trawl designs and operation (i.e. reduced towing and steaming speeds) (Parente *et al.*, 2008). Although clearly validated improvements, many of these modifications require large capital investment and have rarely been implemented without legislation (Jennings and Revill, 2007).

It is well-established that to successfully develop and introduce new fishing techniques to improve sustainability, there is a need to incorporate the fishers' perspective in the subsequent design and/or testing (Kennelly and Broadhurst, 2002). Fishers are more likely to use new techniques if they perceive realised benefits, and there is limited capital investment (Jennings and Revill, 2007). Applying cheap methods to improve sustainability is especially pertinent for small-scale/artisanal fisheries like penaeid otter trawling because they are associated with the greatest bycatch rates (Kelleher, 2005). One possible alternative for improving species selection in some such fisheries is to simply substitute the otter boards for a lightweight beam; the presence of which can produce sufficient stimuli to direct some swimming fish away from the mouth of the trawl (Broadhurst *et al.*, 2012). Equally important, a beam should also reduce both drag and seabed-habitat impacts—owing to relatively less contact by the parallel sleds (Broadhurst *et al.*, 2012).

However, one potential issue for fishers associated with removing otter boards from penaeid-trawl systems is that any reduction in substrate penetration (and therefore 'total-system contact'), could result in fewer penaeids being dislodged and herded into the trawl (e.g. Broadhurst *et al.*, 2012; 2014). It may be possible to address this issue by increasing the trawl footrope length, which can be justified from an environmental point of view because it is generally accepted that otter boards inflict relatively more habitat damage (Gilkinson *et al.*, 1998). It is also possible that despite some increase in footrope length and the inclusion of a beam and two sleds, the system could still have relatively lower drag than using a smaller trawl with otter boards (since otter boards can contribute up to 40% of the total drag of some configurations; Sterling, 2000), although the boundaries of such a relationship remain unknown.

Irrespective of the spreading mechanism, it may also be possible to also improve the size and especially species selectivity of penaeid trawls via simple modifications within existing configurations. For example, because it is well established that sweep wires (between the spreading mechanism and the trawl; Figure 2. 1a) can herd fish inwards (e.g. Engås and Godø, 1989; Andrew *et al.*, 1991) their removal could reduce catches. Additionally, like a rigid beam and as suggested by Broadhurst *et al*. (2012) horizontal vibrating wires and/or obstructions across the mouth of the trawl might herd fish away, either via visual or tactile responses (e.g. Main and Sangster, 1983). Fish are known to respond to both visual and auditory stimuli (Ladich and Fay, 2012), but there is a paucity of research exploiting such behaviour to promote their avoidance of penaeid trawls. Such research is important, since intuitively, modifications that facilitate avoidance are likely to be associated with lower unaccounted fishing mortality than those that promote escape from the codend (Broadhurst *et al.*, 2006).

Considering the above, the aims of this chapter were to investigate the potential for simple within and between system modifications for improving the environmental efficiency of small penaeid trawls. Specifically, I sought to compare (i) the relative catching and engineering performances of trawls spread by either otter boards or a beam and concurrently (ii) the effectiveness of the presence or absence of sweep wires for the otter trawl and a novel modification involving a horizontal wire across the mouth of the beam trawl. To more closely standardise total-system contacts (i.e. accounting for the loss of substrate penetration by the otter boards), the footrope lengths of the beam trawls were increased. The work was done in Australia, but the results have broader implications among national and international small-scale penaeid-trawl fisheries.

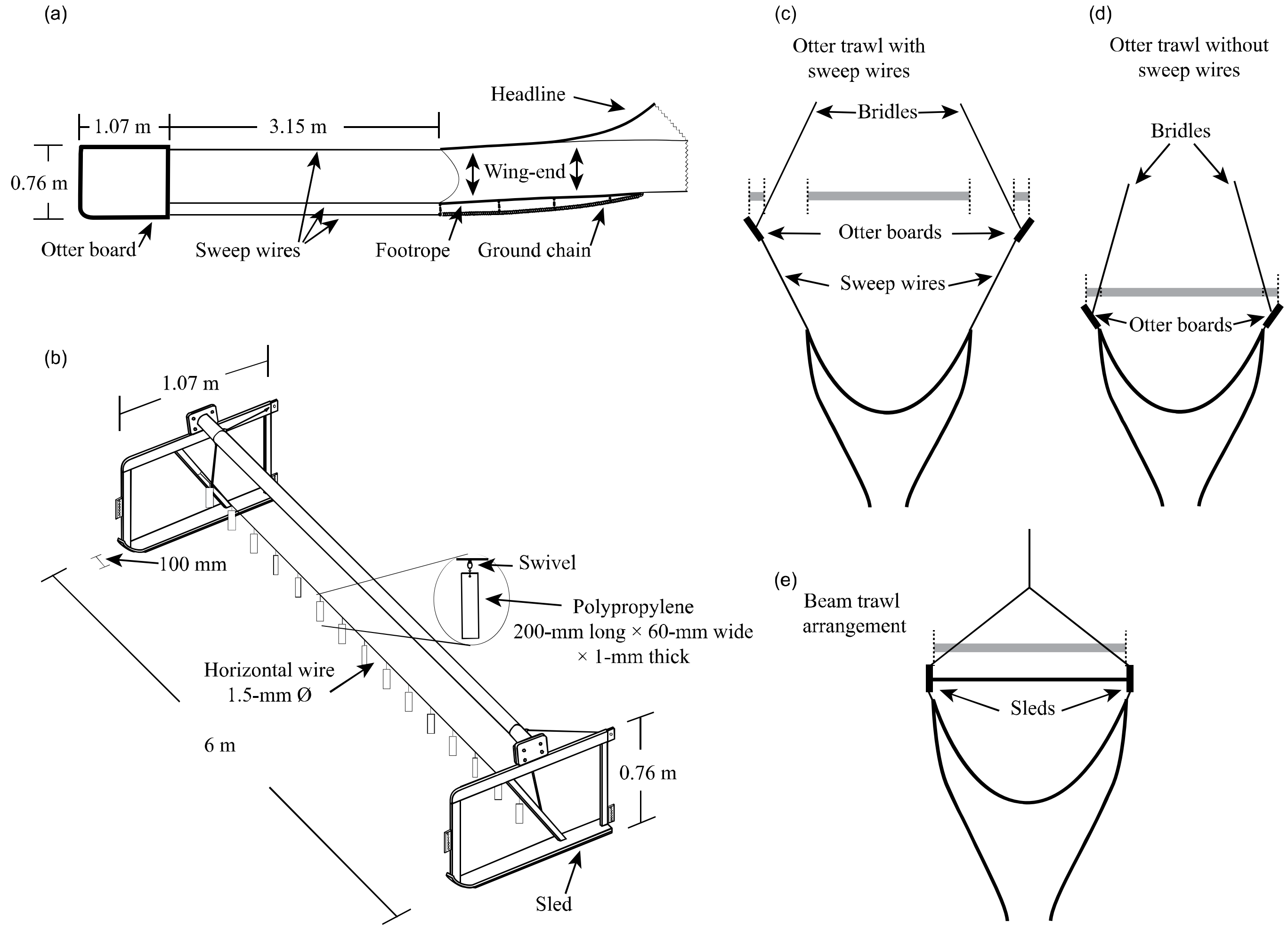

Figure 2. 1. Schematic representation of (a) an otter board and wing-end section, (b) the beam with a highlighted view of an individual strip of a polypropylene, and (c–e) each spreading-mechanism configuration during deployment. The shaded areas between the parallel dashed lines represent total-system contacts.

Material and methods

Fishing vessel, monitoring equipment and tested treatments

The experiment was completed in the Lake Wooloweyah estuary (29° 26’S 153° 22’E; sand and mud substrata ~ 1–2 m depth) during summer 2013 using a 10-m double-rigged trawler (104-kw). The trawler had 40-m bridles (6-mm diameter–Ø stainless-steel wire) on a two-drum hydraulic winch, and was equipped with: a global positioning system (GPS; Lowrance, HDS5) to record speed over the ground (SOG in m s^{-1}); fuel monitor (Floscan series 9000); sum log (model: Bronze + Log) to record speed through the water (STW in m s^{-1}); and attachable load cells (Amalgamated Instrument Company; model no. PA6139) to measure the combined tension (kgf) in the paired bridles, which were always deployed to 12 m. Where required (see below) replicate measures of the wing-end spreads of relevant trawls were obtained using Notus paired wireless sensors. The data from the sensors were received through an omnidirectional hydrophone and logged onto a laptop. All electronic data were recorded every 60 s.

Two identical beam assemblies (each 108 kg) were built; each comprising an aluminium yacht mast (6.00 m long × 0.14 m wide × 0.08 m deep) and galvanised-steel sleds (1.07 m long × 0.76 m high × 0.10 m base plates; Figure 2. 1b). The beam length was based on the maximum considered operationally practical by the fisher. Two pairs of cambered, stainless-steel otter boards (each 1.07 m long × 0.76 m high × 54 kg in air total weight) were also constructed. A beam configuration and pair of otter boards were assigned to one side of the trawler throughout the experiment.

Four trawl bodies—two each of 7.35-m (labelled A and B) and 9.19-m (C and D) headline and footrope lengths—were constructed from the same nominal 42-mm (stretched mesh opening−SMO) mesh (identical 1.25-mm Ø twisted polyethylene−PE twine) for use with the paired otter boards and each beam, respectively (Figure 2. 2). All trawls had a posterior circumference of 150 transversals (T) (50 T for the top and bottom panels and 25 T for each side panels; Figure 2. 2). The headline length of the beam trawl was calculated based on a hypothesised spread ratio (proportion of wing-end spread to headline length) of 0.65 for the otter trawl−derived from a model proposed by Sterling (2000). All trawl bodies were rigged with identical Nordmøre-grids (28-mm bar spacing) in extension sections comprising nominal 40-mm PE mesh (2.50-mm Ø twisted twine) and square-mesh codends made from nominal 27-mm polyamide (PA) mesh (1.25-mm Ø twine) hung on the bar (see Broadhurst *et al.*, 2012 for specifications). The twine areas were 4.80 and 6.38 m^2 for each trawl (comprising body, extension and codend) attached to the otter boards and beam, respectively.

Total system areas were calculated as the sum of the twine, ground gear, sweep wires (if present), frame lines, catch (0.23 m^2) and either the otter boards (× 2) or the beam-and-sled areas, and were 6.99 and 7.48 m^2 for each otter- and beam-trawl configuration.

Experimental design

Prior to starting the work, the four trawl bodies, extensions and codends were checked for mesh uniformity by measuring 15 replicate SMOs using a local, purpose-built gauge. In total, four treatments (two within each spreading mechanism) were deployed in four-day blocks (with replicate 40-min deployments for each treatment) over 12 days. The treatments included the otter trawls (i) with and (ii) without three sweep wires (each 6-mm Ø stainless-steel wire and 3.15 m long between each otter board and wing-end; Figure 2. 1a, c and d); and the beam trawls (iii) with and (iv) without a horizontally strung 1.50-mm Ø stainless-steel wire. I hypothesised that adding the horizontal wire would evoke an escape response among fish and removing the sweep wires would herd fewer fish into the net (Figure 2. 1b-e). The horizontal wire was attached to the centre of the sleds 0.35 m below the 6-m beam and in front of the trawls (Figure 2. 1b). Secured to the wire (0.40 m apart) using swivels were flat strips of green polypropylene (200 mm long × 60 mm wide × 1 mm thick) (Figure 2. 1b).

On each day, one of the above four spreading-mechanism treatments was assigned to a side of the vessel where it remained for one day in each four-day block. One of the two designated trawls within each spreading mechanism was then attached and deployed either three times (on the beam), or two or four times (on the otter boards) after which trawls (within spreading mechanisms) were swapped. The pairs of the Notus sensors were randomly assigned to the A and B otter trawls for two consecutive deployments, before being swapped. Throughout the experiment, each pair of Notus sensors was used 36 times (18 times on each trawl). Load cells were assigned to each Notus-sensor pair and followed their sampling order on the otter trawls, and were similarly rotated among the beam-trawl deployments.

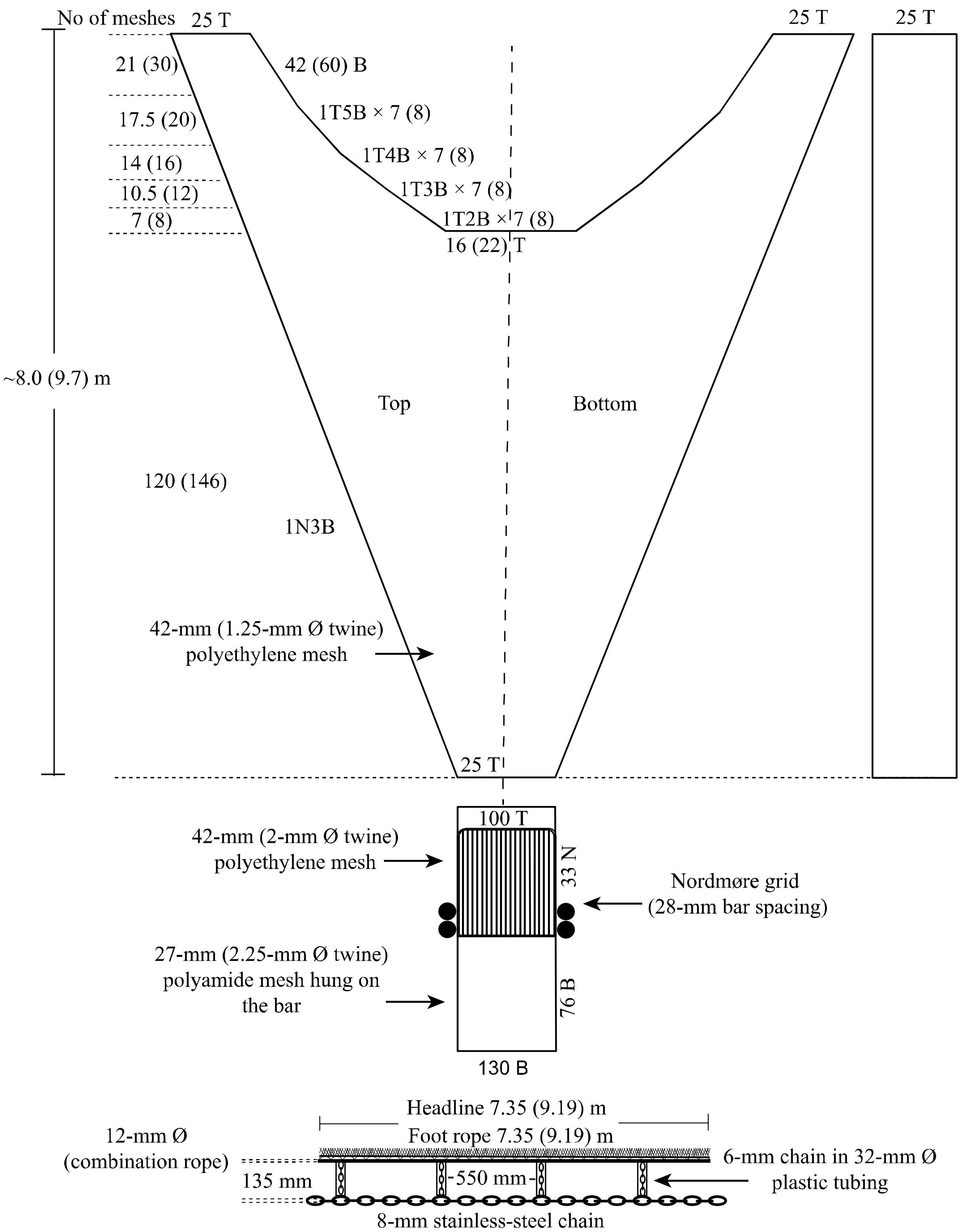

Figure 2. 2. Plans of the 7.35- (labelled A and B) and 9.19-m (C and D; inside parentheses) trawl bodies used in the experiment. T, transversals; B, bars; N, normals; and Ø, diameter.

At the end of each deployment, the two codends were simultaneously emptied onto a partitioned tray and the catches separated, with the total weights of penaeids and bycatch recorded along with the numbers or weights (see below) of each bycatch species for each trawl. Total lengths (TL to the nearest 0.5 cm) of the most abundant teleosts were also recorded. A random sample of ~500 g of penaeids was collected and then separated by species in the laboratory. Numbers and weights were recorded and ~100 individuals of the most abundant species (school prawns, *Metapenaeus macleayi* (Haswell) —see Results) were measured for their carapace lengths (CL to the nearest 1 mm). These data were used to estimate the totals (numbers and weights) of each penaeid species in each deployment for *M. macleayi*. In addition to the living bycatch, all debris were recorded by weight.

Data analyses

To confirm the homogeneity of the four trawls, the hypothesis of no differences in the SMOs of the various bodies, extensions and codends was tested in a linear model (LM). The remaining biological and technical data collected during fishing were analysed to test the general assumption of no differences among the four spreading-mechanism treatments, but in different formats. For each deployment, the numbers and weights of catches were treated in their unstandardised form (i.e. 40-min^{-1} deployment), and also after being standardised to ha^{-1} trawled using the area of footrope contact (i.e. average wing-end spread × the distance trawled).

Additionally, in an attempt to explain variability among the numbers and weights of *M. macleayi* between the beam and otter trawls (see Results), the latter data were also standardised to the total-system contact area (i.e. (average wing-end spread + span of otter-board contact) × the distance trawled), where the span of each otter-board contact was calculated by multiplying the otter-board length (1.07 m) by the sine of the angle of attack (AOA; calculated from the predicted wing-end spread of each configuration and using the model proposed by Sterling (2000). This is a deterministic model of trawl performance that will always produce the same output from a given starting condition. Because the sweep wires were above the substrate, they were not included in total system contact (Figure 2. 1a). Similarly, the relatively thin (0.10 m) sled-base plates of the beams were outside the wing-ends and parallel to the tow direction, and so for these configurations the footrope and total-system contacts were considered synonymous (Figure 2. 1e).

All (i) unstandardised and standardised catch data using the (ii) footrope and (iii) total-system contacts of the various configurations were then log-transformed to account for an assumed multiplicative relationship with causal factors, and analysed in separate linear mixed models (LMMs), with the fixed effect of 'spreading-mechanism configuration' and appropriate random factors (‘days’, ‘trawls’, ‘deployments’ × days, and ‘sides’ of the vessel). Other biological data, including the mean CL of *M. macleayi* and replicate drag per deployment were analysed untransformed. Engineering data, including the area trawled, wing-end spread for the otter trawls, spread ratio and drag were also analysed untransformed, and with appropriate covariates, including SOG and STW, and a variable termed ‘current’ created by the difference between the two. The models were fitted using the lmer function from the lme4 package in R 2.15.3 (The R Project for Statistical Computing; http://www.r-project.org/) and the significance of trawl configuration determined using a likelihood ratio test (LRT). Any significant differences detected for spreading-mechanism configuration were subsequently explored using pairwise comparisons in conjunction with the Benjamini–Hochberg–Yekutieli procedure to control the false discovery rate (FDR; Benjamini and Yekutieli, 2001).

Predicted means from the LMMs for drag were used to calculate relative fuel consumption associated with towing the four treatments. Specifically, assuming that for any given towing speed, the concomitant fuel usage was proportional to the drag, it is possible to determine the relative fuel consumption rate. Fuel consumption was standardised to ha^{-1} trawled and kg^{-1} of *M. macleayi* caught for each trawl design by comparing the predicted fuel consumption rate with predicted mean wing-end spread (the rate at which area was being swept for a given trawl speed), and the predicted mean absolute (per 40-min deployment) *M. macleayi* catches from the respective LMMs.

Results

Over 12 days, 36 deployments of each spreading-mechanism configuration were completed, catching ~519 and 132 kg of penaeids (nearly all were *M. macleayi*) and fish bycatch, respectively (Table 2. 1). The bycatch comprised 40 species, although more than 89% of the total included southern herring, *Herklotsichthys castelnaui* (Ogilby) (5.0–18.5 cm TL; 46.3%), yellowfin bream, *Acanthopagrus australis* (Owen) (4.0–24.5 cm TL; 12.3%), tailor, *Pomatomus saltatrix* (Linnaeus) (2.5–15.0 cm TL; 10.1%), Ramsey’s perchlet, *Ambassis marianus* (Günther) (3.0–11.0 cm TL; 8.9%), silver biddy, *Gerres subfasciatus* (Cuvier) (3.0–14.5 cm TL; 6.8%), and Australian anchovy, *Engraulis australis* (White) (3.0–9.0 cm TL; 4.9%) (Table 2. 1). Blue blubber jellyfish, *Catostylus mosaicus* (Quoy and Gaimard) was also common (Table 2. 1), while debris were restricted to empty shells of *Anadara trapezia* (Deshayes) and *Spisula trigonella* (Lamarck) (~101 kg total). Analyses of catch data were limited to the variables above, and only those of interest were graphed.

In addition to shells, the wing-end meshes of the trawls without sweep wires accumulated more sediment than the other three configurations. These clogged meshes formed an ~ right-angle triangle with a base extending ∼2.5 m along the footrope.

Engineering performances

The SMOs were not significantly different between trawls, extensions or codends, with overall means ± SE of 41.25 ± 0.08, 41.40 ± 0.17, and 27.35 ± 0.10 mm, respectively (LM, $p > 0.05$). There was a significant effect of spreading-mechanism configuration on wing-end spread that manifested as a significantly greater spread ratio (SR) for the otter trawl without sweep wires (0.71 ± 0.01; or a predicted mean of 5.25 ± 0.04 m) than with sweep wires (0.67 ± 0.01 or 4.96 ± 0.04 m) and, irrespective of sweep wires, both otter-trawl configurations were spread at significantly greater ratios than the beam trawl (both 0.65 ± 0.00 or 6.00 ± 0.00 m, LMM and FDR, $p < 0.05$; Tables 2. 2−4). Within the otter-board configurations, the absence of sweep wires increased the AOA by 3° (Table 2. 3).

Drag was also significantly affected by spreading-mechanism configuration, although in addition to the random variables assessed above for wing-end spread the parsimonious model also included SOG, which presented as a positive relationship irrespective of configuration (LMM, $p < 0.001$, Table 2. 2). Predicted mean drags for spreading-mechanism configuration are presented at the centred value of SOG (m s^{-1}), that were derived from the range of logged data for the otter trawl with (0.93–1.95 m s^{-1}) and without sweep wires (0.77–1.95 m s^{-1}) and the beam trawl with (0.93–1.95 m s^{-1}) and without (0.77–1.80 m s^{-1}) a horizontal wire. Compared to both otter-trawl configurations, the beam trawls had significantly lower drags (predicted means reduced by 27–31%; FDR, $p < 0.001$; Tables 2. 3 and 4). In terms of fuel, this equated to ~2.8 and ~2.2 L ha^{-1} for footrope and total-system contacts respectively for both otter-trawl configurations, with the beam trawls using ~1.8 L ha^{-1} for footrope/total-system contacts (Table 2. 3).

Table 2. 1. Scientific and common names and numbers (except blue blubber jellyfish—weights in kg only) of organisms caught during the experiment.

Family	Scientific name	Common name	Total
Cnidarians			
Catostylidae	*Catostylus mosaicus*	Blue blubber jellyfish	78
Crustaceans			
Palaemonidae	*Macrobrachium novaehollandiae*	Freshwater prawn	37
Penaeidae	*Metapenaeus macleayi*	School prawns[1]	223,722
	Metapenaeus bennettae	Green tail prawn[1]	267
	Penaeus monodon	Tiger prawn[1]	39
	Peneaus plebejus	Eastern king prawn[1]	1,102
Portunidae	*Portunus armatus*	Blue swimmer crab[1]	19
	Scylla serrata	Giant mud crab[1]	2
Elasmobranch			
Dasyatididae	*Dasyatis* sp	Stingray	44
Molluscs			
Loliginidae	*Uroteuthis* sp	Squid	253
Teleosts			
Ambassidae	*Ambassis jacksoniensis*	Port Jackson glassfish	128
	Ambassis marianus	Ramsey's perchlet	859
Antennariidae	*Antennarius striatus*	Striate anglerfish	1
Apogonidae	*Siphamia roseigaster*	Pink-breasted siphonfish	124
Ariidae	*Arius graeffei*	Forktail catfish[1]	74
Carangidae	*Caranx sexfasciatus*	Bigeye trevally[1]	6
Clupeidae	*Herklotsichthys castelnaui*	Southern herring[1]	4,460
	Hyperlophus vittatus	Whitebait[1]	46
Eleotridae	*Gobiomorphus australis*	Striped gudgeon	4
Engraulidae	*Engraulis australis*	Australian anchovy	470
Gerreidae	*Gerres subfasciatus*	Silver biddy[1]	660
Gobiidae	*Arenigobius bifrenatus*	Bridled goby	10
Hemiramphidae	*Arrhamphus sclerolepis*	Snubnose garfish[1]	1
	Hyporhamphus regularis	River garfish[1]	12
Monacanthidae	*Aluterus monoceros*	Unicorn leatherjacket	1
Monodactylidae	*Monodactylus argenteus*	Diamond fish	19
Mugilidae	*Liza argentea*	Flat-tail mullet[1]	26
	Mugil cephalus	Bully mullet[1]	197
Muraenesocidae	*Muraenesox bagio*	Common pike eel	1
Paralichthyidae	*Pseudorhombus arsius*	Largetooth flounder[1]	12
Platycephalidae	*Platycephalus fuscus*	Dusky flathead[1]	5
Plotosidae	*Euristhmus lepturus*	Long-tailed catfish[1]	86
Pomatomidae	*Pomatomus saltatrix*	Tailor[1]	971
Priacanthidae	*Priacanthus macracanthus*	Red bigeye	2
Sciaenidae	*Argyrosomus japonicas*	Mulloway[1]	2
Sillaginidae	*Sillago ciliata*	Sand whiting[1]	7
Soleidae	*Synclidopus macleayanus*	Narrow banded sole	13
Sparidae	*Acanthopagrus australis*	Yellowfin bream[1]	1,184
	Rhabdosargus sarba	Tarwhine[1]	31
Terapontidae	*Pelates quadrilineatus*	Trumpeter[1]	29
Tetraodontidae	*Tetractenos glaber*	Toadfish	147
Tetrarogidae	*Notesthes robusta*	Bullrout	8

[1]economically important

Table 2. 2. Summaries of likelihood ratio test (LRT) statistics from linear mixed models assessing the importance of the fixed effect of spreading-mechanism configuration (otter trawls with and without sweep wires, and beam trawls with and without a horizontal wire) in explaining variability among engineering and biological variables. Numbers and weights were analysed 40-min^{-1} deployment and standardised to ha^{-1} trawled calculated using the footrope contact (average wing-end spread × distance trawled) and, additionally for *Metapenaeus macleayi*, the total-system contact ((i.e. wing-end spread + span of otter-board contact) × the distance trawled) and then log-transformed.

Variables	LRT
Engineering variables	
Wing-end spread	38.01***
Drag	20.78***
Biological variables	
Wt of school prawns *Metapenaeus macleayi* 40 min^{-1}	20.24***
Wt of *M. macleayi* ha^{-1} of footrope contact	23.95***
Wt of *M. macleayi* ha^{-1} of total-system contact	20.76***
No. of *M. macleayi* 40 min^{-1}	21.14***
No. of *M. macleayi* ha^{-1} of footrope contact	24.49***
No. of *M. macleayi* ha^{-1} of total-system contact	24.11***
Mean CL of *M. macleayi*	8.36*
Wt of blue blubber jellyfish *Catostylus mosaicus* 40 min^{-1}	10.67*
Wt of *C. mosaicus* ha^{-1}of footrope contact	5.92
Wt of empty shells 40 min^{-1}	88.29***
Wt of empty shells ha^{-1} of footrope contact	89.36***
Wt of fish bycatch 40 min^{-1}	16.79***
Wt of fish bycatch ha^{-1} of footrope contact	21.14***
No. of fish bycatch 40 min^{-1}	13.13**
No. of fish bycatch ha^{-1} of footrope contact	17.32***
No. of southern herring *Herklotsichthys castelnaui* 40 min^{-1}	22.30***
No. of *H. castelnaui* ha^{-1} of footrope contact	24.72***
No. of yellowfin bream *Acanthopagrus australis* 40 min^{-1}	3.86
No. of *A. australis* ha^{-1} of footrope contact	4.83
No. of tailor *Pomatomus saltatrix* 40 min^{-1}	4.61
No. of *P. saltatrix* ha^{1} of footrope contact	3.19
No. of Ramsey's perchlet *Ambassis marianus* 40 min^{-1}	1.31
No. of *A. marianus* ha^{-1} of footrope contact	1.68
No. of silver biddy *Gerres subfasciatus* 40 min^{-1}	1.73
No. of *G. subfasciatus* ha^{-1}of footrope contact	3.07
No. of Australian anchovy *Engraulis australis* 40 min^{-1}	2.16
No. of *E. australis* ha^{-1} of footrope contact	1.29

*$p < 0.05$
**$p < 0.01$
***$p < 0.001$

Table 2. 3. Summary of predicted mean ± SE wing-end spreads (m), spread ratios, drags (kgf), and other mean performance indicators for the four spreading-mechanism configurations. Litres of fuel ha^{-1} were calculated using both the footrope (FRC–average wing-end spread × distance trawled) and total-system contacts (TSC−average wing-end spread + otter board span on the bottom) × distance trawled). Mean predicted drags were derived with a centred value of SOG and with zero current. Dissimilar superscript letters indicate significant differences detected in false-discovery-rate pairwise comparisons ($p < 0.001$).

	Otter trawl with sweep wires	Otter trawl without sweep wires	Beam trawl without a horizontal wire	Beam trawl with a horizontal wire
Otter board angle of attack (°)	36	39	na	na
Wing-end spread (m)	4.96 (0.04)^{A}	5.25 (0.04)^{B}	6.00 (0.00)^{C}	6.00 (0.00)^{C}
Spread ratio	0.67 (0.01)	0.71 (0.01)	0.65 (0.00)	0.65 (0.00)
Drag (kgf)	142.59 (30.71)^{A}	148.26 (30.66)^{A}	102.18 (26.58)^{B}	103.56 (30.73)^{B}
Fuel rate (L h^{-1})	6.738	7.075	5.224	5.294
Fuel intensity				
L ha^{-1} (FRC)	2.808	2.808	1.804	1.810
L ha^{-1} (TSC)	2.235	2.235	1.804	1.810
L kg^{-1}	0.990	1.237	1.008	1.320

Table 2. 4. Summary of the acceptance (A) or rejection (R) of the null hypothesis (of no difference in the relative performance) for key response variables among the various pair-wise comparisons of the four treatments of interest; (i) otter trawl with sweep wires (O with W), (ii) otter trawl without sweep wires (O without W), (iii) beam trawl with a horizontal wire (B with W), and (iv) beam trawl without a horizontal wire (B without W).

Ho = no difference in the relative performance

Pairwise comparison	Penaeids	Bycatch	Drag
O with W vs O without W	A	R	A
O with W vs B without W	R	R	R
O with W vs B with W	R	R	R
O without W vs B without W	R	A	R
O without W vs B with W	R	A	R
B with W vs B without W	R	A	A

Catching performances

Spreading-mechanism configuration significantly affected the catches of *M. macleayi* and their sizes, fish bycatch, *H. castelnaui* and empty shells across all categories (i.e. 40-min^{-1} deployment and ha^{-1} trawled) and the weight of *C. mosaicus* 40-min^{-1} deployment (LMM, $p < 0.05$; Tables 2. 2 and 4, Figures 2. 3a and b and 2. 4a−d). Subsequent FDR pair-wise comparisons revealed that in terms of catches 40-min^{-1} deployment, both otter-trawl configurations caught the same quantities of *M. macleayi* ($p > 0.05$) but significantly more (predicted mean increases of up to double) than the beam-trawl configurations ($p < 0.05$; Figure 2. 3a and b). Further, within beam-trawl configurations, the presence of the horizontal wire was associated with a significant reduction in catches of *M. macleayi* (by 21%; FDRs, $p < 0.05$; Figure 2. 3a and b). These differences were maintained for standardised catches, except that the otter trawl with sweep wires caught significantly more *M. macleayi* than without for both footrope and total-system contacts (by up to 29%; FDRs, $p < 0.05$; Figure 2. 3a and b). In terms of *M. macleayi* sizes, the beam trawl with the horizontal wire caught significantly larger CLs (by up to 0.5 mm) than the otter trawl without sweep wires (FDR, $p < 0.05$), but there were no other pairwise differences (FDRs, $p > 0.05$; Figure 2. 4). Both the otter trawl with sweep wires and the beam trawl without the horizontal wire had similar fuel intensities for *M. macleayi* (at ~1.0 L kg^{-1}), while the otter trawl without sweep wires and the beam trawl with the horizontal wire operated at 1.2 and 1.3 L kg^{-1}, respectively (Table 2. 3).

The FDR pair-wise comparisons for fish bycatch showed that the otter trawl with sweep wires caught a significantly greater weight (1.6–2.0 times) 40-min^{-1} deployment, and number (up to 2.0 times) and weight (up to 2.4 times) ha^{-1} of footrope contact, than the other three spreading-mechanism configurations ($p < 0.01$; Figure 2. 5a and c). By comparison, for the number of fish bycatch 40-min^{-1} deployment, the otter trawl with sweep wires similarly caught significantly more (by up to 1.6 times) than the otter trawl without sweep wires and the beam trawl with the horizontal wire (FDR, $p < 0.01$), but not the beam trawl without the horizontal wire (FDR, $p > 0.05$; Figure 2. 5c).

For the most abundant fish species, *H. castelnaui*, compared to all other spreading-mechanism configurations, the beam trawl with the horizontal wire retained significantly fewer 40-min^{-1} deployment (predicted means reduced by 47–69%) and ha^{-1} of footrope contact (by 49–75%, FDR, $p < 0.01$; Figure 2. 5d). The predicted mean numbers of other abundant fish, including *P. saltatrix* and *A. australi*s, were not significantly different among spreading-mechanism configurations (LMM, $p > 0.05$; Figure 2. 5e and f). By comparison, both beam-trawl configurations retained significantly greater weights (1.7 times) of *C. mosaicus* 40-min^{-1}

deployment than the otter trawls (FDR, $p < 0.01$), but no significant differences were detected for standardised catches (FDR, $p > 0.05$; Figure 2. 5b). The otter trawl without sweep wires retained significantly more shells (99%) than the other three configurations for both 40-min^{-1} deployment and standardised catches (FDR, $p < 0.001$)

Discussion

The results from this chapter reiterate the utility of modifying penaeid-trawl anterior sections for improving their ecological efficiencies measured here as reductions in bycatch and drag, and therefore the fuel rate and intensity (Sumpton *et al.*, 1989; Broadhurst *et al.*, 2012; 2014; Table 2. 4). The observed differences between- and within-spreading mechanism configurations can be discussed according to the key underlying engineering changes and possible species-specific responses, and ultimately used to provide directions for ongoing research.

There were clear between-system drag differences which highlight the important contribution of the otter boards to the relevant cumulative total drag. Specifically, despite their 25% longer headline lengths (and associated 33% greater twine area) and not withstanding slight differences in spread ratio (see below), the beam-trawls had significantly lower drags (up to 31%, corresponding to ~ 1.9 L less fuel h^{-1}) than the otter trawls. By considering the tension in the towing warp and the sweep wires (calculated from netting drag), the total hydrodynamic forces and the ground shear, it is possible to estimate the contribution of the otter boards towards total system drag at ~45% (Sterling, 2000). Understanding the extent of such a contribution is important, since irrespective of between-system changes, simple alterations to the design (e.g. foil shape and aspect ratio) or configuration (e.g. AOA) of existing otter boards could improve trawl efficiency.

While more detailed investigations of otter-board performance in response to rigging arrangements/configurations are required, it is evident that simply removing the sweep wires significantly increased wing-end spread and with some (albeit non-significant) increase in drag (the predicted mean was 6 kg greater). This result can be attributed to a slight reduction in bridle angle caused by a narrower total gear span as the sweep wires were removed. The lower bridle angle meant that less overall spreading force from the otter boards was required, with the surplus simply increasing SR.

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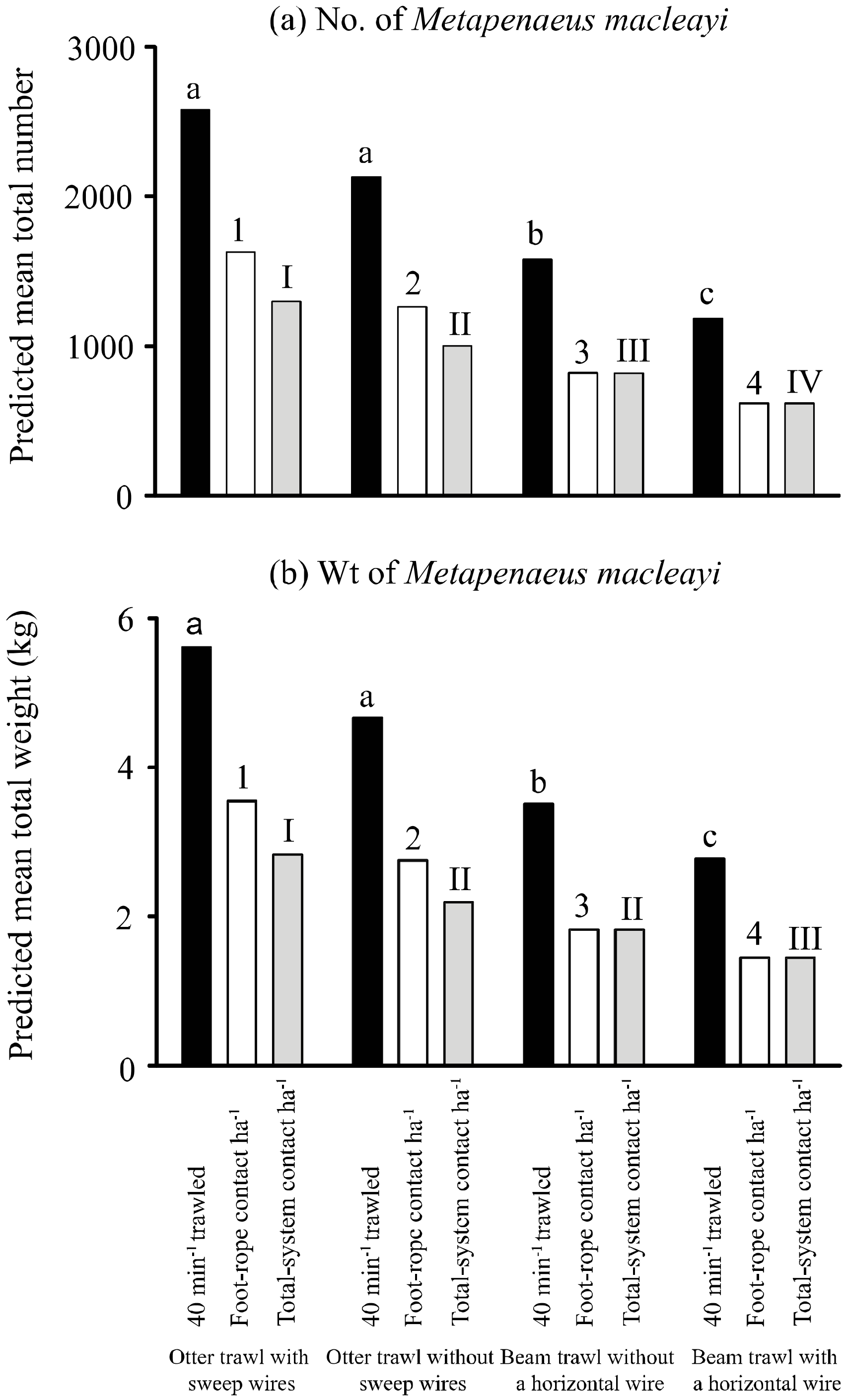

Figure 2. 3. Differences between the four spreading-mechanism configurations for predicted mean (a) numbers and (b) weights of school prawns, *Metapenaeus macleayi* 40-min^{-1} deployment, and standardised to ha^{-1} trawled using the footrope (average wing-end spread × distance trawled) and the total-system contacts ((wing-end spread + span of otter-board contact) × the distance trawled). Dissimilar, letters, numbers and roman numerals above the histograms indicate significant differences detected in false-discovery-rate pairwise comparisons ($p < 0.05$).

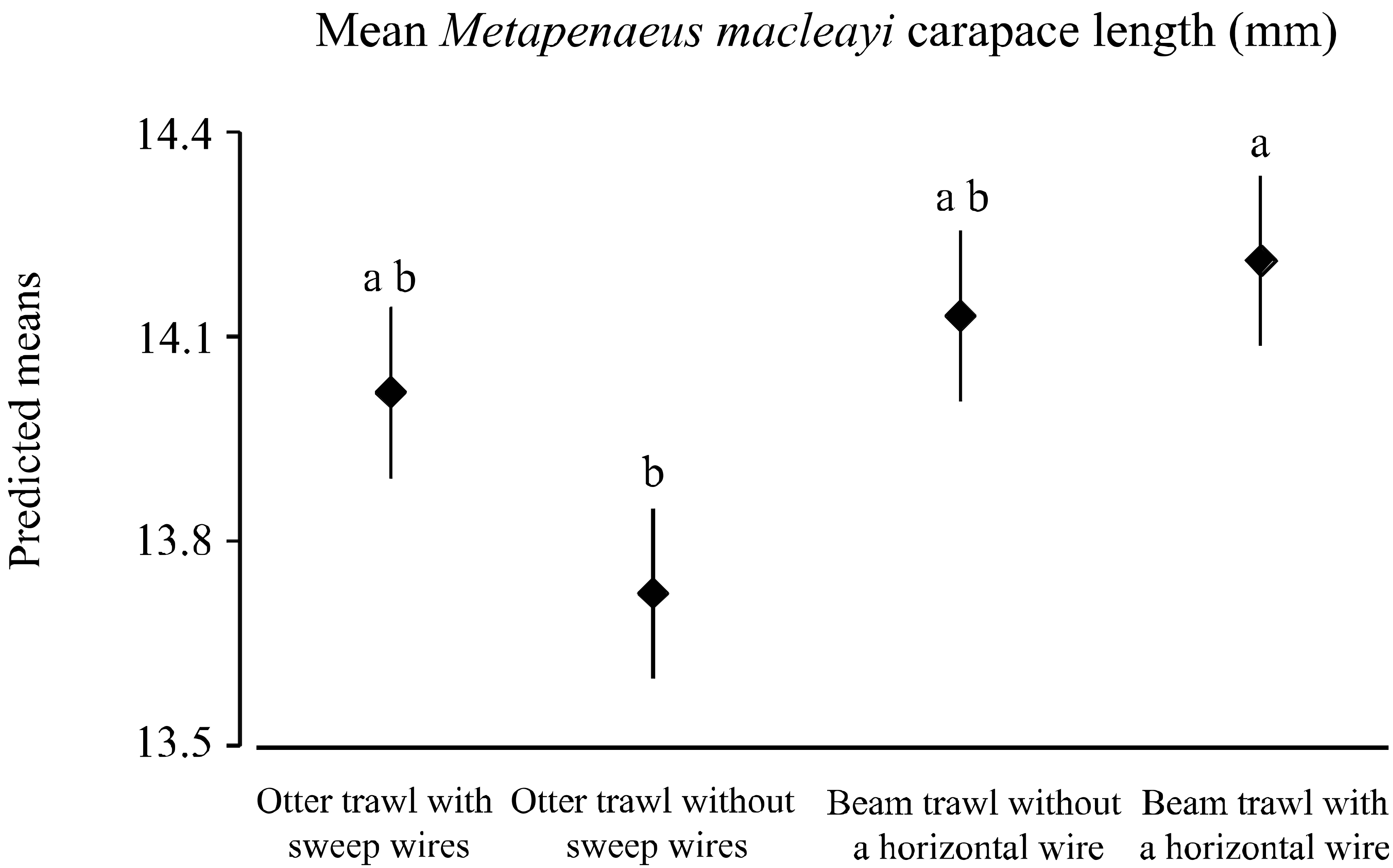

Figure 2. 4. Predicted mean (±SE) carapace lengths for school prawns, *Metapenaeus macleayi* 40-min^{-1} deployment for the four spreading-mechanism configurations. Dissimilar letters above the histograms indicate significant differences detected in false-discovery-rate pairwise comparisons (p < 0.05).

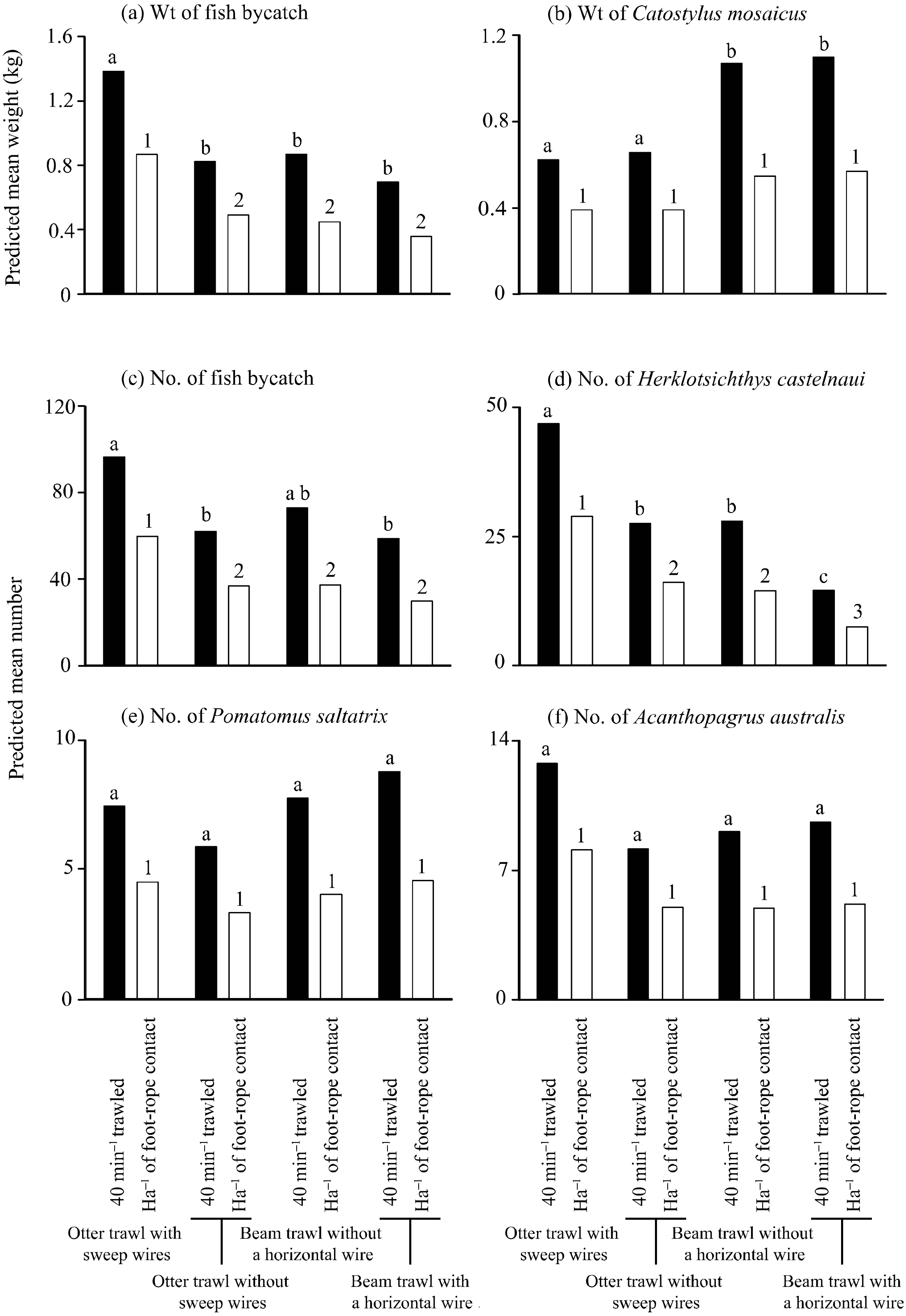

Figure 2. 5. Differences in predicted mean weights of (a) fish bycatch and (b) blue blubber jellyfish *Catostylus mosaicus*, and the numbers of (c) fish bycatch, (d) southern herring, *Herklotsichthys castelnaui*, (e) tailor, *Pomatomus saltatrix*, and (f) yellowfin bream, *Acanthopagrus australis* 40-min^{-1} deployment and standardised to ha^{-1} trawled using the footrope contact (average wing-end spread × distance trawled) for the four spreading-mechanism configurations. Dissimilar letters and numbers above the histograms indicate significant differences detected in false-discovery-rate pairwise comparisons ($p < 0.05$).

Irrespective of the sweep wires, both otter-trawl configurations also had greater SRs than the beam trawls (i.e. predicted mean differences of 0.02 and 0.06). Such differences warrant consideration, not only in terms of engineering performances but also relative catching efficiencies. For example, in a recent study Broadhurst *et al*. (2014) showed that compared to beam trawls rigged at a SR of 0.5, the same designs configured at between 0.6 and 0.8 caught significantly fewer *M. macleayi* and fish per trawled ha. One explanation for this result was that the corresponding steeper wing angles increased the probability of mesh encounters and escape for *M. macleayi* and were less efficient for herding fish (Broadhurst *et al.*, 2014).

While the possibility for confounding effects of SR exist here, it was considered either unlikely or of minimal importance for two reasons. First, the maximum difference between SRs here was a lot lower than those tested by Broadhurst *et al*. (2014) (e.g. 9 vs 25−60%) and so the geometric consequences might also be minimal. Second, unlike the earlier study and independent of all other variables, positive correlations were observed between catches of both *M. macleayi* and *H. castelnaui* (the only teleost significantly impacted by any of the treatments) and SR. Assuming few confounding SR effects, the observed differences in catches can be attributed to the key treatment effects of interest: the spreading mechanisms and within-system changes.

For some variables, including the non-responsive shell debris and *C. mosaicus*, the direct consequences of the above within- and between-system engineering changes were evident in their absolute catches (per 40-min deployment). For example, removing the sweep wires meant that shells disturbed by the otter boards were directed into the wings, instead of passing anteriorly, while the beam-trawl configurations caught more *C. mosaicus*, simply because of the longer headline. However, such simple trends were not apparent for the other key species—results that probably reflect behavioural responses to stimuli and therefore need to be discussed in terms of standardised catches (to remove the confounding effects of different swept areas).

With respect to *M. macleayi* behaviour, it is well established that most individuals reside in or on the substrate during the day (Ruello, 1973). Other studies have shown that the typical response of such benthic-orientated penaeids to external stimuli is to contract their abdomen, which in the case of a contact with a footrope, propels them upwards and into the trawl mouth (Watson, 1989). After subsequent contractions (and random propulsions) within the trawl, individuals were observed to attempt to orientate back into the substrate, but inevitably were directed by the panels of netting into the codend (Watson, 1989).

Like the footrope, otter boards might be expected to disturb *M. macleayi* and potentially direct some towards the approaching trawl (Broadhurst *et al.*, 2012; 2014). In this chapter, I attempted to test this hypothesis by also standardising *M. macleayi* catches to total-system contact (which included the span of the otter-board baseplates on the substrate), although the otter trawls still retained significantly more *M. macleayi* than the beam trawls. However, such a result could indicate that otter boards are more than 100% efficient for their span. For example, owing to their weight, otter boards penetrate the substrate more deeply than the footrope, and are thus likely to disturb more buried organisms (Kaiser *et al.*, 2002).

The potential behavioural response of *M. macleayi* to the otter boards might also explain why there was a significant reduction in catches and a bias towards smaller individuals in the absence of sweep wires. Removing the sweep wires would reduce the opportunity for any *M. macleayi* disturbed by the otter boards to settle back into the substrate before being overtaken by the trawl. It is also possible that because the swimming ability of individuals might be proportional to their size (e.g. Daniel and Meyhofer, 1989), some of the larger *M. macleayi* disturbed by the otter boards might have escaped over the headline, explaining the observed size differences.

Although speculative in the absence of *in situ* observations, the observed size bias and significant reduction in *M. macleayi* catches by the beam trawl with the horizontal wire might be explained by similar behaviour as above. The length and likely motion of the plastic strips meant that they could have disturbed the substrate anterior to the trawl mouth and in doing so, may have stimulated some *M. macleayi* before they encountered the ground gear, facilitating their escape.

Like for *M. macleayi*, species-specific behavioural responses could explain the observed differences in catches of *H. castelnaui* between and within spreading mechanisms. For example, previous studies have identified positive relationships between sweep wire length and fish catches, although the effects can be quite species-specific; potentially reflecting a range of variables, including swimming performances, and perhaps responses to visual or tactile stimuli (Engås and Godø, 1989; Wardle, 1989; Andrew *et al.*, 1991). The results here support this trend with *H. castelnaui* the only species (of the six assessed) that significantly responded to the horizontal or sweep wires.

The differential, consistent response of *H. castelnaui* to the between- and within-system changes might reflect their extensive schooling behaviour. Other schooling species (e.g. gadoids and a scombrid) have been observed to orientate equidistant between those components offering the greatest stimuli (e.g. the otter boards and sweep wires) with their subsequent retention in trawls influenced by their swimming capacity and endurance (Main and Sangster, 1983). If the same stimuli affected *H. castelnaui*, then removing the sweep wires or adding a horizontal wire might be expected to negatively and positively affect the extent of reactions and therefore catches, depending on behavioural reactions in front of the trawl.

Trawling primarily relies on visual stimulus in the catching process, but fish reactions depend on a mixture of stimuli from the various trawl components (Main and Sangster, 1983; Glass and Wardle, 1989). For example, the colour and contrast of the gear will impact the visual senses while parts of the rigging (e.g. chains and shackles) will provide their own unique auditory signals, with tactile responses likely when visual stimuli are reduced or absent (Main and Sangster, 1983; Glass and Wardle, 1989). While the visual stimulus were standardised within treatments (e.g. the netting material and the spreading mechanisms within configurations were identical) the modifications would have disrupted consistency. Further research is required to more closely assess the stimuli evoking a response in *H. castelnaui* and also to elicit responses among other key species. Part of this work should include assessments of the utility of the above modifications at night (e.g. when many penaeid-trawl fisheries operate) because visual cues will be reduced (Andrew *et al.*, 1991; Walsh, 1996).

Irrespective of the actual mechanisms contributing to the differences in catches, this study has important implications for ongoing work to improve the environmental efficiency of trawls. Specifically, choosing an appropriate sweep wire length (at least for penaeid trawls fished during the day) could represent a simple mechanism for improving species selectivity. Similarly, like for the beam trawl, it might be possible to extend a horizontal wire between otter boards. As part of this work, the hypotheses that any wires (either horizontal or sweep) provide auditory signals as they move through the water should be investigated.

With rising costs (e.g. fuel) and high unaccounted fishing mortality, applying appropriate modifications to penaeid trawls to improve fuel efficiencies and size and species selectivity has never been more pertinent. The results presented here illustrate the utility of within-system modifications to the anterior sections of penaeid trawls that are simple and require limited capital investment, but ultimately should contribute towards resolving the components of the above issues. Such characteristics support ongoing research.

Chapter 3: A 'simple anterior fish excluder' (SAFE) for mitigating penaeid-trawl bycatch

Published in *Public library of Science One* (McHugh, M. J., Broadhurst, M. K., Sterling, D. J. and Millar, R. B. (2015) A 'simple anterior fish excluder' (SAFE) for mitigating penaeid-trawl bycatch. *PloS One* **10**(4): e0123124.)—incorporated in Appendix 3.

Abstract

Various plastic strips and sheets (termed 'simple anterior fish excluders'−SAFEs) were positioned across the openings of penaeid trawls in attempts at reducing the unwanted bycatches of small teleosts. Initially, three SAFEs (a single wire without, and with small and large plastic panels) were compared against a control (no SAFE) on paired beam trawls. All SAFEs maintained targeted school prawn, *Metapenaeus macleayi* (Haswell), catches, while the largest plastic SAFE significantly reduced total bycatch by 51% and the numbers of tailor—*Pomatomus saltatrix* (Linnaeus), bully mullet—*Mugil cephalus* (Linnaeus) and southern herring—*Herklotsichthys castelnaui* (Ogilby) by up to 58%. A redesigned SAFE ('continuous plastic') was subsequently tested (against a control) on paired otter trawls, significantly reducing total bycatch by 28% and *P. saltatrix* and *H. castelnaui* by up to 42%. The continuous-plastic SAFE also significantly reduced *M. macleayi* catches by ~7%, but this was explained by ~5% less wing-end spread, and could be simply negated through otter-board refinement. Further work is required to refine the tested SAFEs, and to quantify species-specific escape mechanisms. Nevertheless, the SAFE concept might represent an effective approach for improving penaeid-trawl selectivity.

Keywords: SAFE, bycatch reduction, fish excluder, otter trawling, penaeids

Introduction

The capture and mortality of unwanted organisms (termed 'bycatch') by mobile demersal fishing gears is a global issue affecting many fisheries (Kelleher, 2005). This is especially the case for penaeid trawling, which despite contributing only ~1.5% towards the total global marine wild harvest (estimated at a plateau of ~80 m t since 1985 (FAO, 2012)), accounts for >25% of all discarded bycatch (~7.3 m t per annum (Kelleher, 2005)); typically comprising small teleosts (<20 cm total length−TL), crustaceans and cephalopods (Kelleher, 2005; Broadhurst *et al.*, 2006). Historically, the mortality of such discards has raised wide-spread concerns, and primarily because of the potential for deleterious impacts on subsequent stocks (Alverson and Hughes, 1996; Crowder and Murawski, 1998).

Considerable research has been done to mitigate penaeid-trawl bycatch and associated mortalities (Broadhurst, 2000; Hall *et al*., 2000). Beyond temporal and spatial closures (Hall *et al*., 2000) the greatest efforts have focussed on retrospectively fitting 'bycatch reduction devices' (BRDs) to existing trawls. Broadly, such BRDs can be separated into two categories according to their principle separating function: those that rely on species-specific differences in size (termed 'mechanical-type BRDs'; e.g. the 'Nordmøre-grid'); or behaviour ('behavioural-type BRDs'; e.g. strategic 'square-mesh panels') to either actively or passively separate catches (Broadhurst, 2000).

Notwithstanding their different classifications, the majority of BRDs are located in the posterior trawl (i.e. codend) and compared to conventional configurations can maintain penaeid catches within a ~10% loss, while reducing unwanted bycatches by ~30−70% (Broadhurst, 2000). Such results are positive, although there remains very little information on the mortality of organisms escaping BRDs (and therefore their ultimate benefit); primarily because accurate assessments are difficult, if not impossible, for many fisheries (Davis, 2002; Bayse *et al*., 2014). However, because BRDs that facilitate the rapid escape of organisms with minimal physical contact (e.g. behavioural-type designs) should evoke low mortalities, an even more appropriate concept might be to anteriorly locate designs, and so promote complete trawl avoidance.

While the widespread use of such anterior BRDs is relatively uncommon, there have been successful attempts at demonstrating their utility (Seidel and Watson, 1978). For example, Seidel and Watson (1978) designed a 'fish barrier', comprising mesh webbing across the trawl mouth that precluded the entry of large organisms, and used electrical stimulation to force penaeids up through an open benthic panel, and into the trawl. However, while this configuration had great potential, subsequently cheaper and more easily adaptable (to existing trawl codends) BRDs might have contributed towards its lack of commercial uptake. Also, some mesh-barrier designs (e.g. seal mitigation devices; (Hooper *et al.*, 2005), placed at the trawl mouth can clog (e.g. with seaweed), which could either prevent penaeids entering or, alternatively, reduce wing-end spread and the area trawled (Eayrs, 2007).

The latter issue raises an important consideration. It is well established that complex BRDs are much less likely to be adopted and/or used correctly than those that are inexpensive and/or simple to maintain and operate (Broadhurst, 2000). Consequently, in terms of reducing unaccounted fishing mortality, the wide-scale use of simple and even marginally effective BRDs ultimately will have greater benefits than the limited use of far more effective designs. Given the above, an alternative to completely physically obstructing the trawl mouth may be to insert a behavioural-type BRD, which although being the less effective category of BRDs (Broadhurst, 2000) should be smaller and less likely to affect trawl performance. While the concept of anterior behavioural-type BRDs is not new (e.g. Eayrs, 2007; Ryer, 2008; McHugh *et al*., 2014), the difficulty remains in focusing on the stimuli (e.g. visual or auditory) that will elicit the greatest response among non-target individuals without impacting on target species (Winger *et al*., 2010).

Irrespective of the BRD location (anterior or posterior) or type (behavioural or mechanical), during development there always should be an emphasis on hypotheses testing within a strong empirical experimental design (Hurlbert, 1984). To maximise penaeid catches while minimizing bycatch, any modifications should be clearly identified through systematic testing within the full range of possibilities (Brewer *et al*., 1998; Broadhurst *et al*., 2007). Methodically assessing modifications will facilitate further testing, acceptance or reassessment if the desired result is not achieved (Brewer *et al*., 1998).

During a recent study in an Australian penaeid-trawl fishery, an anteriorly located BRD was tested that met some of the technical criteria discussed above (McHugh *et al*., 2014). Termed the ‘simple anterior fish excluder’ (SAFE), the design comprised a wire between beam-trawl sleds, from which 200- × 60- × 1-mm plastic strips were hung on universal swivels (allowing spinning). Compared to the control, the trawl with the SAFE reduced the catches of one species, southern herring, *Herklotsichthys castelnaui* (Ogilby) by 48%, with minimal effect on catches of the targeted school prawns, *Metapenaeus macleayi* (Haswell).

Here, I expand on the SAFE concept by first assessing the limits of practicality and effectiveness (including the original SAFE tested by McHugh *et al*., 2014) within a beam-trawl configuration before using this information to develop a prototype for testing on a more dynamic (i.e. non-rigid spreading mechanism) otter trawl. Specifically, my aims were to (i) test the hypothesis of no differences in the effectiveness of the SAFE area (i.e. 1, 3 and 11% of the two-dimensional opening) on the beam trawl and then, using this information, (ii) design and test an appropriate SAFE for use in otter trawling. The work was done in Australia, but the results have broader implications among other national and international crustacean-trawl fisheries.

Material and methods

Ethics statement

The research was done in Lake Wooloweyah (29°26′ S 153°22′ E) New South Wales (NSW) Australia and in accord with the Department of Primary Industries scientific collection permit (No. P01/0059(A)-2.0). No specific permissions were required for access to Lake Wooloweyah. This study did not involve endangered or protected species, and all fish were returned to the water as soon as practicable, following each trawl deployment. Animal ethics approval for the research was granted by the NSW DPI Animal Care and Ethics Committee (Ref. 08/06). This study complied with all relevant regulations pertaining to the conservation of the surrounding environment and nearby wildlife, as detailed in the scientific collection permit.

Location and vessel

Two experiments were completed in the Lake (sand and mud substrata ~1–2 m depth) during the Austral summer, 2013 on-board a 10-m double-rigged penaeid trawler (104 kw). The trawler had a global positioning system (Lowrance, HDS5) and two independent sum logs (model: Bronze + Log) to record speed over the ground (SOG) and through the water (STW; both in m s^{-1}). Load cells (Amalgamated Instrument Company; model no. PA6139) were configured so that they could be attached to bridles (always deployed to 12 m from paired winches) to measure the combined tension (kgf). The wing-end spreads of relevant otter trawls were obtained using Notus paired wireless sensors (see below). Data from the Notus sensors were received through an omnidirectional hydrophone and logged onto a laptop. All electronic data were recorded every 60 s.

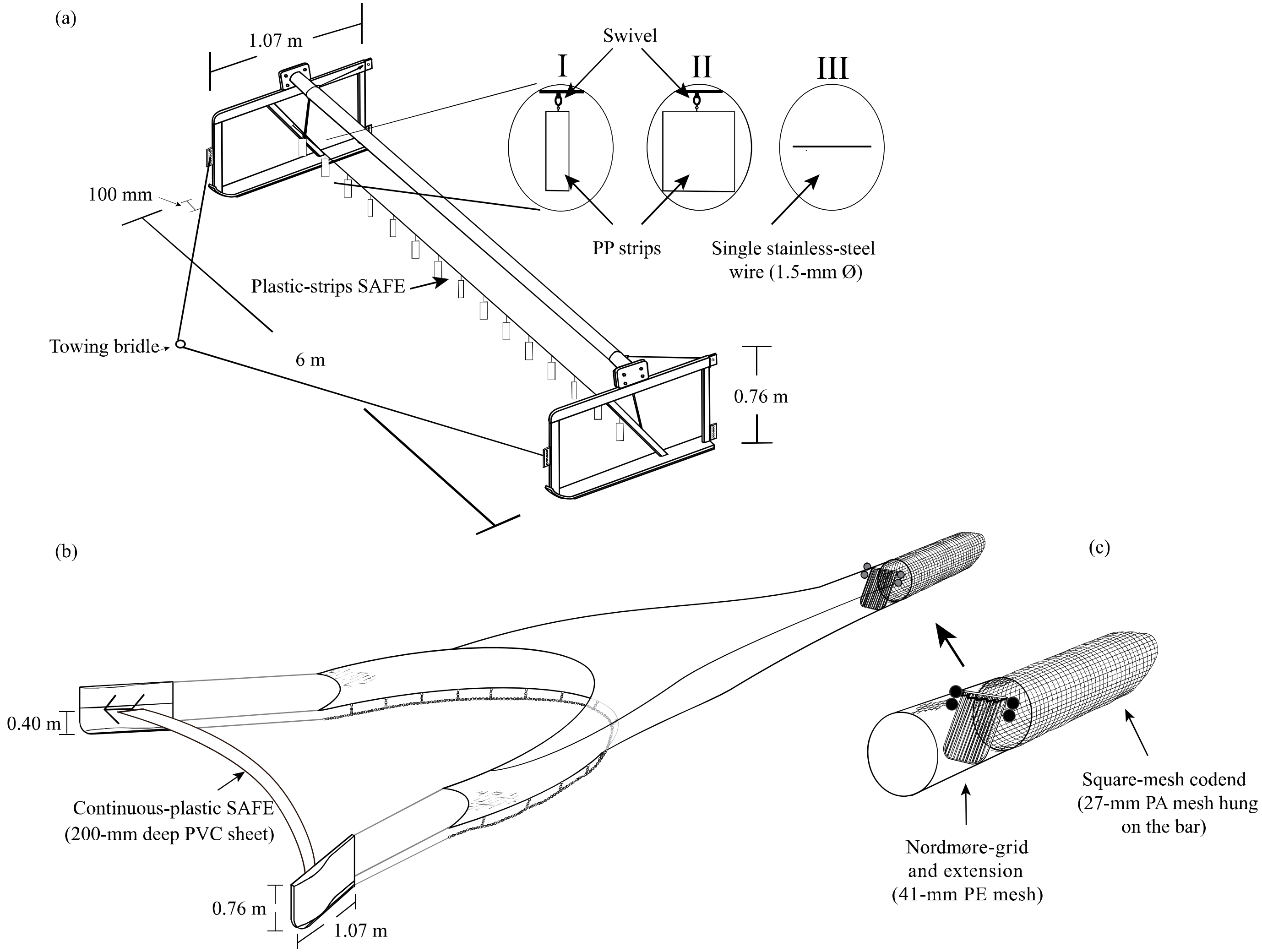

Figure 3. 1. Schematic representation of the (a) beam trawl showing towing bridle and attachment locations of the (I) small-plastic (polypropylene–PP) (60 × 200 × 1 mm), (II) large-plastic (PP) (200 × 200 × 1 mm) and (III) the single-wire (1.50-mm Ø stainless steel) simple anterior fish excluders (SAFEs) tested in experiment 1 and (b) otter trawl with the polyvinyl chloride (PVC) continuous-plastic SAFE tested in experiment 2. The extension (with Nordmøre-grid) and codend (c), used in both experiments, are highlighted. PA, polyamide; PE, polyethylene.

Experiment 1: testing three different SAFEs on a beam trawl

For the first experiment, the trawler was rigged with identical, paired 6-m beam-and-sled (1.07 × 0.76 × 0.1 m; 108 kg) assemblies. These spreading mechanisms were anteriorly attached to the towing wires via a 7.3 m bridle (Figure 3. 1a) and posteriorly to trawl bodies with 9.19 m headlines (and footropes) and constructed from nominal 41-mm mesh (stretched mesh opening–SMO) and 1.25-mm diameter−Ø twisted polyethylene (PE) twine (for a trawl plan, see (McHugh *et al.*, 2014). Both trawl bodies had identical conventional Nordmøre-grids (28-mm bar spacing) and square-mesh codends (120 × 75 bars) made from nominal 27 mm SMO polyamide mesh (1.25-mm Ø twine) hung on the bar (Figure 3. 1b). The Nordmøre-grids and square-mesh codends are mandated in this NSW penaeid fishery.

Three SAFE treatments were constructed; all stretched between the sleds at 0.3 above the baseplates (Figure 3. 1a). The first treatment comprised a single 6-m long, 1.50-mm Ø stainless-steel wire (termed 'single wire') while the second and third had the same wires, but also included 12 evenly distributed flat strips (all 0.2 m long) of 1-mm thick green polypropylene (PP) that were either 0.06- (termed 'small plastic' and the same as those tested by McHugh *et al*. (2014) or 0.2-m ('large plastic') wide (Figure 3. 1a). The PP strips were secured to the main line by a snap-lock (ball bearing) swivel that was attached midway along their leading edges (Figure 3. 1a). Prior to the experiment, the small- and large-plastic strips were secured at several (e.g. centre, edge and middle) attachment points to a pole, which was pulled through the water (at ~1.50 m s^{-1}) alongside a wharf and filmed with a Hero 3^+ GoPro. The plastic strips attached at the centre of their leading edges were observed to spin erratically.

On each fishing day, the paired beams were configured as either the control (i.e. no wire), or with one of the three SAFE treatments and deployed for 40 min. The control and SAFE treatments were then alternated, so that I completed one paired comparison of all four configurations on each day (i.e. six daily deployments). The two trawls were also swapped from side-to-side after the first three deployments, while the load cells were daily rotated from side-to-side. Over seven days, 21 replicate deployments were completed of each SAFE and the control.

Experiment 2: testing a SAFE on an otter trawl

During the second experiment, the beam trawls were replaced with otter trawls, and the towing wires attached directly to paired cambered otter boards (1.07 × 0.76 m each and a total weight of 108 kg; Figure 3. 1b). Sweep wires (2.89-m) were secured posterior to the otter boards and to 7.35-m headline length trawls that were constructed from the same materials and designs as those in experiment 1 and configured with the exact same Nordmøre-grids and codends (Figure 3. 1b; for a trawl plan see McHugh *et al*., 2014).

A single SAFE treatment was constructed for use with the otter trawls. Termed the ‘continuous-plastic’, this design comprised a hemmed sheet of flexible white polyvinyl chloride (PVC) measuring 0.2 m wide (same as the green PP strips) × 6.4 m long, through which a 7.25-m (1.50-mm Ø) stainless-steel wire was threaded and terminated in snap clips (Figure 3. 1b). The length of the wire was calculated based on an average wing-end spread during previous testing of the two trawls, and this was extrapolated to derive the otter-board spread (McHugh *et al*., 2014). The continuous-plastic SAFE was attached between the otter-board towing points at 0.40 m above the baseplates, so that it extended across the front of the trawl (Figure 3. 1b).

At the start of each fishing day, the Notus paired sensors were attached to the wing ends of the trawls on each side of the vessel. The continuous-plastic SAFE was alternately and randomly clipped in front of one trawl, with both then deployed for 40-min up to six times each day. After three deployments, the trawls were swapped from side-to-side, while the load cells and paired Notus sensors were similarity rotated each day. Over five days, 26 replicate deployments were completed of the control and continuous-plastic SAFE.

Data collected and statistical analyses

All trawl bodies and codends were checked for mesh uniformity by measuring 15 replicate SMOs using a local, purpose-built gauge. Other technical data collected during each deployment in each experiment included the: (i) warp tension (kgf) for each configuration; (ii) the total distance (m) trawled (sleds on and off the bottom – obtained from the GPS); and (iii) SOG and STW (m s^{-1}). Additionally, in experiment 2, data for wing-spread (m) were collected for each deployment.

Biological data collected at the end of each deployment included the: total weights of the targeted *M. macleayi* and bycatch; numbers of each bycatch species; and total lengths (TL to the nearest 0.5 cm) of the most abundant teleosts. Random samples of ~500 g of *M. macleayi* were bagged and transferred to the laboratory, where they were measured (carapace length – CL in mm), weighed and counted. These latter data were used to estimate the total numbers and the mean CLs caught during each deployment.

The hypothesis of no differences in the mesh sizes within the four trawl bodies, and two extensions and codends was tested in a linear model (LM). Within each experiment, the remaining data were analysed in linear mixed models (LMMs), with some standardised prior to analyses. The numbers and weights of catches were analysed 40-min^{-1} deployment and also ha^{-1} trawled (calculated using the known beam- and observed otter-trawl wing-end distances and the distance trawled) and as log-transformed data so that predicted effects would be multiplicative. All other data, including the mean CL of *M. macleayi*, mean TL per deployment of sufficiently abundant teleosts (occurring in >95% of deployments), drag and area and distance trawled were analysed in their raw form.

All LMMs included 'anterior-trawl configuration' (i.e. SAFEs vs. controls) as a fixed effect, while 'trawls', 'sides', 'days' and deployments (within days) were included as random terms. For the LMM assessing drags, 'load cell' was included as an additional random term while additional fixed co-variates included 'SOG', 'STW' (with 'sum-log' as a random term) and 'flow' (calculated as the speed of the current in the direction of travel and defined as SOG–STW). The preferred models were chosen based on forward variable selection with a p-value of 0.05 required for an effect to enter the model. All models were fitted using either the lmer function from the lme4 package or ASReml in R 2.15.3 (The R Project for Statistical Computing; http://www.r-project.org/), with the significance of anterior-trawl configuration determined using a Wald *F*-value. In experiment 1, any significant Wald *F*-values for anterior-trawl configuration were subsequently explored using the Benjamini-Hochberg-Yekutieli procedure to control the false discovery rate (FDR) for multiple pair-wise comparisons (Benjamini and Yekutieli, 2001).

Results

There were no significant differences in the SMO between trawl bodies (means ± SE of 41.25 ± 0.08 mm), extensions (41.40 ± 0.17 mm) or codends (27.35 ± 0.10 mm) (LM, $p > 0.05$). Pooled across experiments, the trawls caught 1753 and 154 kg of *M. macleayi* and total bycatch (Table 3. 1). The total bycatch included 29 species, but in experiment 1, tailor, *Pomatomus saltatrix* (Linnaeus) (5.5–18.5 cm T), bully mullet, *Mugil cephalus* (Linnaeus) (5.5–15.5 cm TL), silver biddy, *Gerres subfasciatus* (Cuvier) (5.0–13 cm TL), Ramsey's perchlet, *Ambassis marianus* (Günther) (3.5–10.5 cm TL), yellowfin bream, *Acanthopagrus australi*s (Owen) (4.0–23.5 cm TL), and southern herring, *H. castelnaui* (6.5–16.5 cm TL) comprised >85% of catches (Table 3. 1). In experiment 2, *A. marianus* (5.0–13.5 cm TL), *P. saltatrix* (4.0–17 cm TL), *G. subfasciatus* (6.5–13.5 cm TL), *H. castelnaui* (5.5–15 cm TL), *A. australi*s (5.0–25 cm TL), and tarwhine, *Rhabdosargus sarba* (Forsskål) (5.5–11 cm TL) were most prevalent (>77%; Table 3. 1). These seven species, along with *M. macleayi*, form the basis of the biological analyses.

Table 3. 1. Scientific and common names and numbers (except blue blubber jellyfish, *Catostylus mosaicus*—weights in kg only) of organisms caught during experiments (Exp.) 1 and 2. −, not present in catches.

Family	Scientific name	Common name	Exp. 1	Exp. 2
Cnidarians				
Catostylidae	*Catostylus mosaicus*	Blue blubber jellyfish	108	40
Crustaceans				
Palaemonidae	*Macrobrachium novaehollandiae*	Freshwater prawn	2	−
Penaeidae	*Metapenaeus macleayi*	School prawn[1]	584,044	147,116
	Metapenaeus bennettae	Green tail prawn[1]	21	49
	Penaeus monodon	Tiger prawn[1]	7	3
Portunidae	*Portunus pelagicus*	Blue swimmer crab[1]	6	6
Elasmobranchs				
Dasyatididae	*Dasyatis* sp	Stingray	–	1
Molluscs				
Loliginidae	*Uroteuthis* sp	Squid[1]	368	201
Teleosts				
Ambassidae	*Ambassis jacksoniensis*	Port Jackson glassfish	324	57
	Ambassis marianus	Ramsey's perchlet	470	1,058
Ariidae	*Arius graeffei*	Forktail catfish[1]	1	22
Apogonidae	*Siphamia roseigaster*	Pink-breasted siphonfish	129	65
Carangidae	*Gnathanodon speciosus*	Golden trevally[1]	1	−
	Pseudocaranx dentex	Silver trevally[1]	−	1
	Trachurus novaezelandiae	Yellowtail scad[1]	1	2
Clupeidae	*Herklotsichthys castelnaui*	Southern herring	400	369
	Hyperlophus vittatus	Whitebait	−	5
Engraulidae	*Engraulis australis*	Australian anchovy	45	13
Gerreidae	*Gerres subfasciatus*	Silver biddy	507	447
Hemiramphidae	*Arrhamphus sclerolepis*	Snubnose garfish[1]	3	4
	Hyporhamphus regularis	River garfish[1]	16	–
Monodactylidae	*Monodactylus argenteus*	Diamond fish	2	6
Mugilidae	*Liza argentea*	Flat-tail mullet[1]	24	3
	Mugil cephalus	Bully mullet[1]	1,046	64
Muraenesocidae	*Muraenesox bagio*	Common pike eel	1	4
Paralichthyidae	*Pseudorhombus arsius*	Largetooth flounder	15	23
Platycephalidae	*Platycephalus fuscus*	Dusky flathead[1]	1	9
Plotosidae	*Euristhmus lepturus*	Longtail catfish	61	175
Pomatomidae	*Pomatomus saltatrix*	Tailor[1]	4,087	937
Scatophagidae	*Selenotoca multifasciata*	Old maid	–	1
Sciaenidae	*Argyrosomus japonicus*	Mulloway[1]	2	2
Sillaginidae	*Sillago ciliata*	Sand whiting[1]	–	2
Soleidae	*Synclidopus macleayanus*	Narrow banded sole	1	−
Sparidae	*Acanthopagrus australis*	Yellowfin bream[1]	420	328
	Rhabdosargus sarba	Tarwhine	65	202
Terapontidae	*Pelates quadrilineatus*	Trumpeter[1]	13	4
Tetraodontidae	*Tetractenos glaber*	Toadfish	8	271

[1]economically important

Table 3. 2. Summaries of Wald *F*-values from linear mixed models assessing the importance of the fixed effect of anterior-trawl configuration (SAFEs vs. controls) in explaining variability among engineering and biological variables. Numbers and weights were analysed 40-min^{-1} deployment and standardised to ha^{-1} trawled calculated using the footrope contact (wing-end spread × distance trawled) and then log-transformed. –, not relevant.

	Experiment 1	Experiment 2
	Wald *F*	Wald *F*
Engineering variables		
Wing-end spread	–	4.19*
Drag	0.62	0.004
Hectare trawled	2.17	22.46***
Biological variables		
Wt of school prawns *Metapenaeus macleayi* 40 min^{-1}	2.53	4.52*
Wt of *M. macleayi* ha^{-1}	2.56	0.19
No. of *M. macleayi* 40 min^{-1}	1.56	1.46
No. of *M. macleayi* ha^{-1}	1.58	0.19
Mean CL of *M. macleayi* 40 min^{-1}	1.55	5.41*
Wt of fish bycatch 40 min^{-1}	22.81***	12.16**
Wt of fish bycatch ha^{-1}	23.54***	7.08*
No. of fish bycatch 40 min^{-1}	19.18**	9.33**
No. of fish bycatch ha^{-1}	19.75***	5.53*
No. of tailor *Pomatomus saltatrix* 40 min^{-1}	15.09***	11.93**
No. of *P. saltatrix* ha^{-1}	17.34***	10.86**
Mean TL of *P. saltatrix* 40 min^{-1}	1.34	–
No. of bully mullet *Mugil cephalus* 40 min^{-1}	5.06**	–
No. of *M. cephalus* ha^{-1}	4.99**	–
No. of southern herring *Herklotsichthys castelnaui* 40 min^{-1}	3.94*	7.00*
No. of *H. castelnaui* ha^{-1}	3.98*	5.73*
No. of silver biddy *Gerres subfasciatus* 40 min^{-1}	1.49	1.66
No. of *G. subfasciatus* ha^{-1}	1.24	2.39
No. of Ramsey’s perchlet *Ambassis marianus* 40 min^{-1}	1.77	0.15
No. of *A. marianus* ha^{-1}	1.45	0.01
No. of yellowfin bream *Acanthopagrus australis* 40 min^{-1}	1.00	0.11
No. of *A. australis* ha^{-1}	1.07	0.38
No. of tarwhine *Rhabdosargus sarba* 40 min^{-1}	–	0.25
No. of *R. sarba* ha^{-1}	–	0.14

*$p < 0.05$
**$p < 0.01$
***$p < 0.001$

Experiment 1: testing three different SAFEs on a beam trawl

The four beam-trawl configurations were towed at similar SOGs and STWs (ranging from 1.23 to 1.28 m s^{-1}) covering predicted mean ± SE areas between 1.90 ± 0.02 and 1.95 ± 0.02 ha 40-min^{-1} deployment, which were not significantly different (LMM, $p > 0.05$; Table 3. 2). None of the SAFEs significantly affected drag (predicted means ± SE between 205.3 ± 2.2 and 208.2 ± 2.2 kg, LMM, $p > 0.05$; Table 3. 2). STW and SOG were both positively correlated with drag, but they were not statistically significant ($p > 0.05$).

Because there were no significant differences in the areas trawled, the biological data provided the same interpretations irrespective of standardization (i.e. to ha^{-1}; Table 3. 2). Consequently, for convenience (and beyond Table 3. 2), only the catches 40-min^{-1} deployment in experiment 1 are discussed and presented.

The anterior-trawl configuration had no significant effects on the catches, nor mean CL of *M. macleayi* (13.86–14.26 mm; LMM, $p > 0.05$), but did significantly influence the number and weight of total fish bycatch, and the numbers of *M. cephalus*, *H. castelnaui* and *P. saltatrix* (LMM, $p < 0.01$; Table 3. 2; Figure 3. 2a−g), but not the mean size of the latter (LMM, $p > 0.05$; Table 3. 2). The significant effects on bycatch broadly were positively correlated with SAFE surface area (Figure 3. 2b, d and e−g). Specifically, compared to the control and the single-wire SAFE, both the small- and large-plastic SAFEs significantly and incrementally reduced the weights (by up to 27 and 51%) and numbers (by up to 26 and 47%) of total fish bycatch (FDR, $p < 0.05$; Table 3. 2, Figure 3. 2b and d). The beam trawl with the large-plastic SAFE also caught significantly fewer *P. saltatrix* and *M. cephalus* than all other configurations (by up to 43 and 58%) and *H. castelnaui* than the control (by 49%; FDR, $p < 0.05$; Table 3. 2, Figure 3. 2e–g). No other fish were significantly affected by the SAFEs, although the numbers of *G. subfasciatus* and *A. australis* followed similar trends as above (LMM, $p > 0.05$; Table 3. 2, Figure 3. 2h and i).

Experiment 2: testing a SAFE on an otter trawl

The parsimonious LMM describing drag included SOG and anterior-trawl configuration as main effects, with the latter not significantly different between the control (259.5 ± 5.0 kg) and SAFE (259.7 ± 5.0 kg) trawls ($p > 0.05$; Table 3. 2). Irrespective of anterior-trawl configuration, SOG was positively associated with drag (LMM, $p < 0.05$).

There was a significant difference in wing-end spreads between configurations, with the control (4.31 ± 0.21 m) spread 0.21 ± 0.05 m wider than the SAFE (LMM, $p < 0.05$; Table 3. 2). Both configurations shared a common negative association with STW (LMM, $p < 0.01$). The control trawl fished a significantly greater area than the SAFE (1.43 ± 0.10 vs. 1.34 ± 0.10 ha) (LMM, $p < 0.001$; Table 3. 2).

The slightly narrower trawl wing-end spread due to the continuous-plastic SAFE was reflected in a significant reduction (~7%) in the weight of *M. macleayi* 40-min^{-1} deployment (LMM, $p < 0.05$; Table 3. 2, Figure 3. 3a). However, when standardised to ha^{-1}, the number and weight of *M. macleayi* were not significantly different between trawls (LMM, $p > 0.05$; Table 3. 2, Figure 3. 3a and c), although the predicted mean CL was significantly smaller in the trawls with the SAFE (14.72 ± 0.20 mm) than the control (14.91 ± 0.20 mm) (LMM, $p < 0.05$; Table 3. 2).

Compared to the control, the trawl with the continuous-plastic SAFE caught significantly less total bycatch by weight (by 28%) and number (24%) and fewer *P. saltatrix* and *H. castelnaui* 40-min^{-1} deployment and ha^{-1} trawled (both by up to 42%) (LMM, $p < 0.05$; Table 3. 2, Figure 3. 3b, and d−f). Catches of the remaining key species were not significantly affected by the continuous-plastic SAFE (LMM, $p > 0.05$; Figure 3. 3g–j).

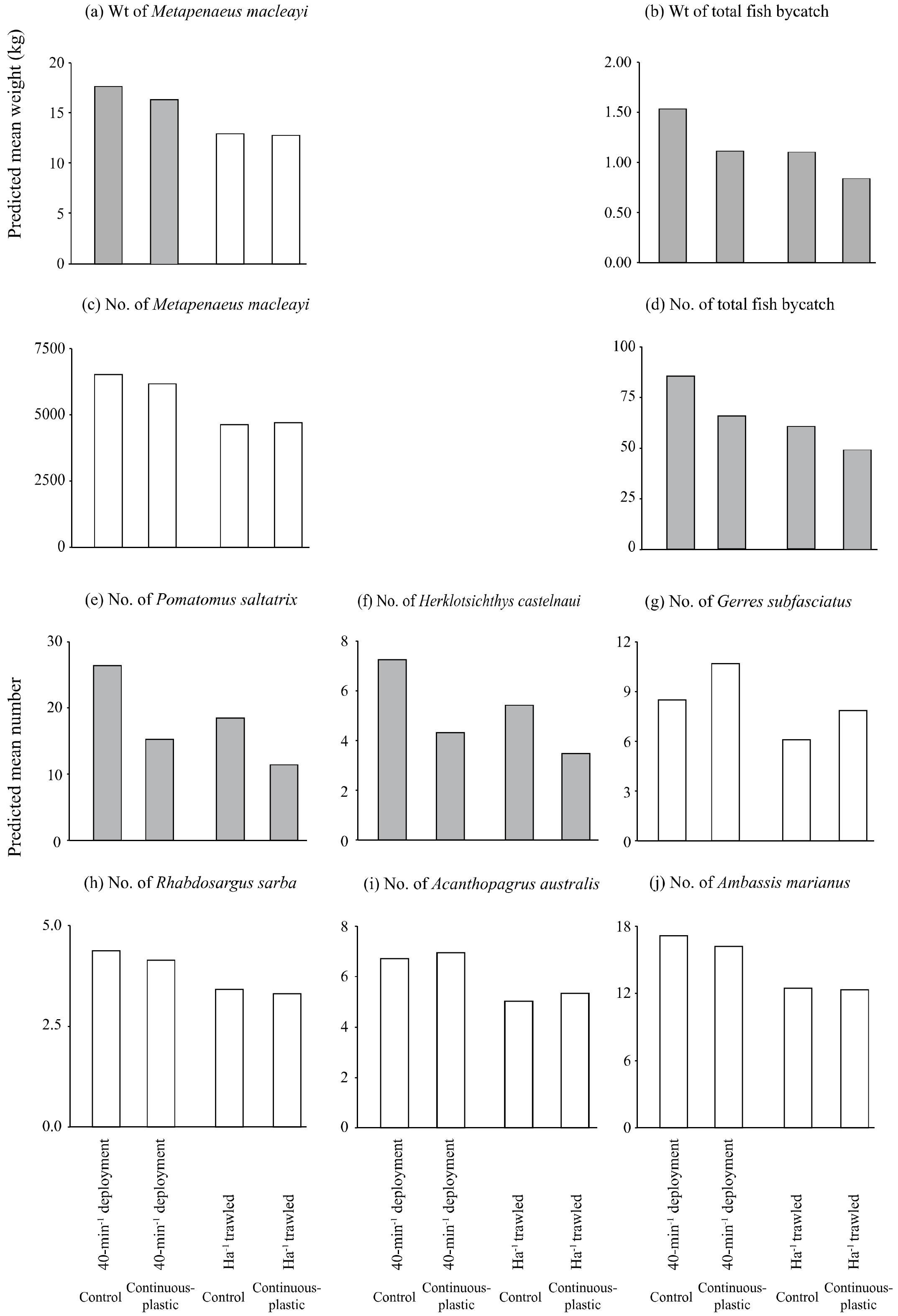

Figure 3. 2. Differences in predicted mean weights of (a) school prawns, *Metapenaeus macleayi*, and (b) total fish bycatch, and the predicted mean numbers of (c) *M. macleayi*, (d) total fish bycatch, (e) tailor, *Pomatomus saltatrix*, (f) bully mullet, *Mugil cephalus*, (g) southern herring, *Herklotsichthys castelnaui*, (h) silver biddy, *Gerres subfasciatus,* (i) yellowfin bream, *Acanthopagrus australi*s and (j) Ramsey's perchlet, *Ambassis marianus* 40-min^{-1} deployment between the control and three SAFEs (single-wire, small-plastic and large-plastic) tested in experiment 1. Shaded histograms indicate significant wald *F*-values, while '>' and '=' indicate differences detected in false-discovery-rate pair-wise comparisons (p < 0.05).

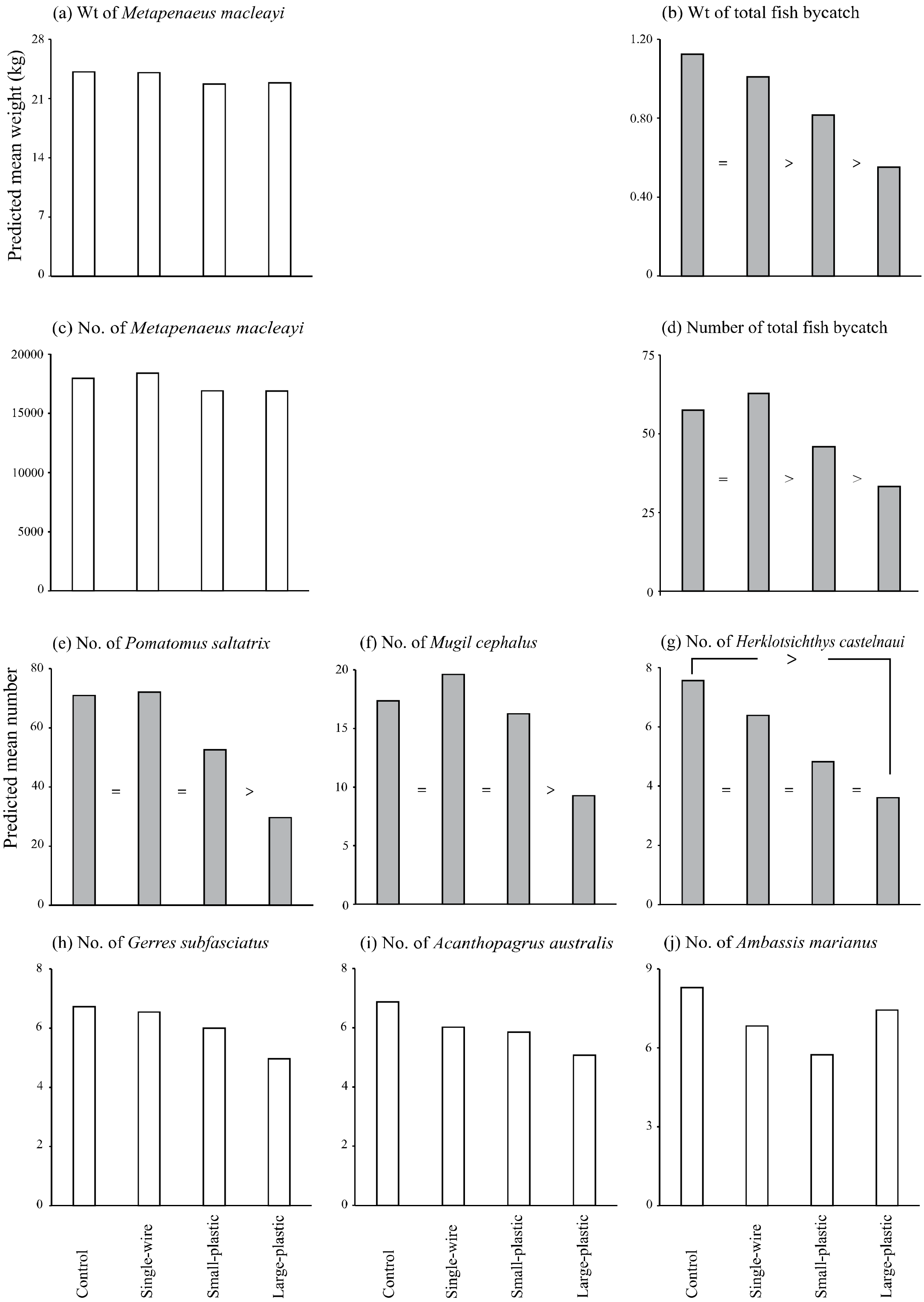

Figure 3. 3. Differences in predicted mean weights of (a) school prawns, *Metapenaeus macleayi*, and (b) total fish bycatch, and the predicted mean numbers of (c) *M. macleayi*, (d) total fish bycatch, (e) tailor, *Pomatomus saltatrix*, (f) southern herring, *Herklotsichthys castelnaui*, (g) silver biddy, *Gerres subfasciatus*, (h) tarwhine, *Rhabdosargus sarba*, (i) yellowfin bream, *Acanthopagrus australis* and (j) Ramsey's perchlet, *Ambassis marianus* 40-min^{-1} deployment and standardised to ha^{-1} trawled using the footrope contact (average wing-end spread × distance trawled) between the control otter trawl and that containing the continuous-plastic SAFE tested in experiment 2. Shaded histograms indicate significant differences detected by Wald *F*-values ($p < 0.05$).

Discussion

This study validates the concept of locating simple BRDs anterior to penaeid trawls for improving their species selectivity (Ryer, 2008; McHugh *et al*., 2014). Like in my earlier, preliminary study (McHugh *et al*., 2014), the SAFEs tested here maintained target catches at acceptable limits and, for the otter trawl, the bycatch reductions rivalled those observed for other traditional posteriorly located BRDs (Broadhurst, 2000). The SAFEs' effectiveness can be discussed firstly according to the utility of the experimental approach, and then the related probable species-specific responses.

The limits/range of the original SAFE concept described by McHugh *et al*. (2014) were somewhat defined in experiment 1 by incrementally testing larger modifications, involving a horizontal wire with and without small and large plastic attachments, across the beam trawl. Specifically, the sizes of the individual plastic strips—∽0.23 m long (PP strip and swivel)—were close to what I considered the maximum in terms of not contacting the top of the beam (0.76 m high), each other, nor the substrate during fishing, and potentially impacting on *M. macleayi* catches. However, notwithstanding the considerable bycatch reduction (up to 51%), the maintenance of *M. macleayi* catches at the same levels as the control, suggest that a slightly larger SAFE might have had some utility. Following this logic, I increased the area (from 11 to 23% of the trawl mouth) in the SAFE used on the otter trawl. Further, because the independent plastic strips comprising the SAFEs used on the beam trawl would have been easily entangled among the otter-trawl components (e.g. otter boards and sweep wires as they came together at the surface after each deployment), a continuous-plastic strip was chosen.

Additionally, compared to the SAFE with individual strips the continuous-plastic SAFE was likely to have less overall impact on the substrate; because there were no independent moving parts. While the likelihood of substrate contact existed, because the width between the otter boards was not constant (i.e. they are more dynamic than the beam trawl's fixed width sleds), it was considered negligible given the slight fluctuation in average otter-board spread (0.21 ± 0.05 m) and the absence of abrasion marks (i.e. I did not observe any).

While the continuous-plastic SAFE did not affect otter-trawl drag, it significantly decreased wing-end spread, the area trawled per deployment, and therefore the catches of *M. macleayi*. The narrower wing-end spread can probably be explained by the drag from the SAFE pulling the otter boards together which would have concomitantly reduced the drag of the trawl and ground gear (Broadhurst *et al*., 2014), providing the observed lack of change in total system resistance. It is also clear that a lower otter-board angle of attack (AOA) would have reduced the effective substrate contact and while speculative, this may have contributed to the negative impacts on *M. macleayi* catches—owing to fewer individuals (potentially those that were larger given the differences in mean size) being disturbed and directed into the path of the trawl (Broadhurst *et al*., 2012). Nevertheless, such catch effects were minimal and could be simply remedied by slightly increasing otter-board surface area.

The differences in wing-end spread due to the continuous-plastic SAFE had no negative effect on fish exclusion, with consistent, significant reductions both 40 min^{-1} and ha^{-1} trawled. The SAFEs also maintained fish reductions between experiments, although the large-plastic SAFE used on the beam was considerably more effective (reducing total bycatch by up to 51% compared to the control) than the continuous-plastic SAFE used on the otter trawl. Although speculative, these results might be explained by the importance of visual cues in affecting fish reactions to towed gears, associated variation in trawl dynamics and potentially other environmental factors (Kim and Wardle, 1998a; 1998b).

Typically, the trawl capture process depends on fish being herded between the otter boards, sweep wires and trawl wings and then when fatigued, falling back into the codend (Main and Sangster, 1981). This process is strongly affected by the elicited visual cues, whereby as water clarity decreases (e.g. low light or turbid conditions) so too does a fish's ability to detect gear-components and instigate an escape response (Kim and Wardle, 1998a; 1998b; Davis, 2002; Walsh and Godø, 2003; Winger *et al*., 2010). Considering the above, in experiment 1 the horizontal wires on the beam remained taut and the plastic strips probably rotated freely and individually, potentially creating a strong visual stimulus for some fish. By comparison, in experiment 2, the continuous-plastic SAFE should have provided less movement and possibly reduced stimulus. Equally important, owing to the shallow concave shape of the SAFE, the angle at the otter boards would have increased, potentially herding some fish in towards the trawl path and negating some of the effectiveness.

Beyond the specific SAFE design, I also suggest that differences in fish density and water clarity may have been important factors contributing towards the observed inter-experimental variation in performances (Walsh and Godø, 2003; Winger *et al*., 2010). For example, all three species affected by the SAFEs, but especially *P. saltatrix*, were caught in large numbers (comprising 73 and 32% of the total catches in each experiment). Potentially, intra-specific reactions within schools contributed towards their escape (Walsh and Godø, 2003). Future research to refine the SAFE would benefit from assessing the relationship between water clarity and effectiveness. However, because the extremely poor water clarity precludes using cameras, such work will require a manipulative-type experimental approach.

While turbidity was not measured, it was assumed to be comparable between experiments based on the trawling intensity occurring in the area at the time. Available meteorological data (www.bom.gov.au) suggest ambient light may have been lower during experiment 2 with three (of five) days having greater than 50% cloud cover compared to three (of seven) in experiment 1. The selectivity of *H. castelnaui* could have been influenced by the lower ambient light level, which limits the ability of some species to detect trawls (Glass and Wardle, 1989).

Irrespective of the variability among performances, the observed bycatch reductions, combined with the simplicity and low cost of a SAFE (which should promote adoption as part of a legislated suite of existing, but more complex BRD designs in this fishery) support ongoing testing and refinement. As part of such work, it would be worthwhile to explore ways in which SAFEs could be engineered to concomitantly improve system engineering (and therefore reduce fuel usage). One potential option might be to use the SAFE to more accurately regulate otter-board AOA. It is well established that otter boards represent a large proportion (up to ∽30%) of trawl-system drag, which directly correlates to their AOA (Sterling, 2000). Most designs have a high AOA (>30^o) to increase stability during deployment, but can have greater operational efficiency at AOAs as low as 20^o (Sterling, 2000). Locating an appropriate length of SAFE at the leading edge of otter boards might achieve a lower AOA, and if so reduce some unnecessary system drag. Given the high global price of fuel, even a slight reduction in drag would help to promote industry adoption of the SAFE concept.

Another modification to improve the utility of the SAFE would be to configure a design that maintains a convex shape (away from the trawl mouth); potentially, helping to disperse fish away from the trawl (Ryer, 2008). While this may be difficult to achieve on an otter trawl (due to configuration constraints) such a design might be applicable on a beam trawl, and warrants further testing.

It is clear that trawl gear has evolved to exploit the behavioural and physiological responses of targeted species, but often with concomitant negative impacts on unwanted catches. Retrospectively fitted BRDs have been, and will continue to remain, an important applied strategy for mitigating bycatches, and ideally their associated unaccounted fishing mortality. Based on the results here, the SAFE concept might represent an effective approach for improving the selectivity of penaeid trawls.

Chapter 4: Comparing three conventional penaeid-trawl otter boards and the new batwing design

Published in *Fisheries Research* (McHugh, M. J., Broadhurst, M. K., Sterling, D. J. and Millar, R. B. (2015) Comparing three conventional penaeid-trawl otter boards and the new batwing design. *Fisheries Research* **167**: 180−189.)—incorporated in Appendix 4.

Abstract

Three experiments were conducted to compare the engineering and catching performances of a hydrodynamic otter board termed the 'batwing' (comprising a sled-and-sail assembly, configured to operate at 20^{o} angle of attack—AOA and with minimal bottom contact) against three conventional designs (termed the 'flat-rectangular'; 'kilfoil' and 'cambered' otter boards) with AOAs between ~30 and 40^{o}. Experiments involved paired penaeid trawls (7.35-m headlines). The first experiment compared the batwing otter boards against all other designs (using 41-mm mesh trawls). In experiment 2, the batwing was tested against the flat-rectangular design (with 32-mm mesh trawls). In experiment 3, the batwing and flat-rectangular otter boards were towed without trawls to facilitate estimates of their partitioned drag. Overall, compared to the conventional otter boards, the batwings had up to ~86 and 18% less bottom contact and drag, respectively. Among the conventional otter boards, the trawls spread by the cambered design caught up to 13% more school prawns *Metapenaeus macleayi* (Haswell); attributed to their greater solid profile. No significant differences were detected among catches of fish in the trawls spread by the various otter boards. The results reaffirm that because otter boards contribute towards a large proportion of total system drag (estimated here at up to ~56%), their appropriate configuration is essential to maximise the fuel efficiency of penaeid-trawl systems.

Keywords: drag, fuel reduction, habitat impacts, otter-board design, penaeids,

Introduction

Penaeids are targeted throughout the world's tropical and temperate regions; mostly using small fishing vessels (<25 m) towing multi-net trawl systems that are laterally spread by paired hydro vanes, called 'otter boards' (Kelleher, 2005; Gillett, 2008). While there is considerable variety among otter-board designs, all encompass a substantial proportion of the entire trawling system weight to ensure sufficient seabed contact, and are orientated at an angle to the tow direction (termed the angle of attack—AOA). The water moving over otter boards creates hydrodynamic forces that horizontally open penaeid trawls to spread ratios (SR) typically 0.6 to 0.8 of their total headline length. The drag component of such hydrodynamic forces has been hypothesised to account for up to 30% of the total-system drag (Sterling, 2000).

At a broad level, the most common otter boards are simple flat, rectangular designs—although more hydrodynamically complex cambered variations are also popular (Seafish *et al*., 1993). Irrespective of design subtleties, the majority of otter boards are rigged to have AOAs between 30 and 40° (Seafish *et al*., 1993; Sterling, 2000). Operating conventional otter boards at such high AOAs helps to maintain their stability, which keeps the other trawl components at optimal efficiency (Patterson and Watts, 1985). Even slight reductions in AOA below this range can result in operational issues, manifesting as reduced stability and possibly lost effective fishing time (Patterson and Watts, 1985; Seafish *et al*., 1993). In an attempt to overcome such issues, a more recent prototype termed the 'batwing' otter board was developed by Sterling and Eayrs (2010) to remain at a constant 20°AOA, and with robust stability achieved through its unique rigging strategy (see Methods).

Although not extensively quantified (but see Patterson and Watts, 1985; 1986), compared to conventional designs, otter boards such as the batwing that have low AOAs should have relatively lower drag for the same spreading force and therefore require less fuel to tow. Calculating the extent of any such fuel reductions is complex. It is well established that the fuel consumed during trawling is proportional to the thrust applied by the trawler, if propeller efficiency remains constant (Prado, 1990). However, the assumption of a proportional relationship between drag reductions and fuel savings remains approximate because many factors affect efficiency, including propeller loading.

Globally, it is becoming imperative to reduce fuel usage in many fisheries including demersal trawling, which has some of the greatest fuel-to-catch ratios, with fuel accounting for 30% of a trawl operator's total costs in developed countries (Suuronen *et al*., 2012). In fact, in Australia, trawlers use at least 55% of their fuel while trawling (with the rest used during travelling between trawl grounds and operating electrical equipment), and are operating close to their profitability threshold (Thomas *et al*., 2010; Wakeford, 2010).

Beyond drag/fuel savings, a potential concomitant benefit of lowering otter-board AOA is reduced benthic contact for any given length (i.e. ∼1.5% for each degree the AOA is lowered), and subsequently fewer associated impacts. For example, an otter board ~1 m long deployed at 40° AOA will impact the bottom for ~64 cm, while at 20° its contact will be reduced to ~34 cm. Even slight reductions in impacts are potentially beneficial, considering that otter boards leave the most discernible track marks from trawl configurations (Caddy, 1973; Kaiser *et al*., 2002). However, from a catching perspective, one concern with minimising otter-board bottom contact is that a lower AOA could reduce substrate disturbance and negatively affect catches because penaeids mostly reside in the substrate (Broadhurst *et al*., 2012; 2013a; McHugh *et al*., 2014). Further, otter boards are known to herd fish (Wardle, 1989), either through visual or tactile stimuli, and so even subtle variation in their design and AOA might influence species selection by the trawl.

Despite the above, there have been very few formal studies of the effects of otter boards on the engineering (e.g. AOA and spreading force) and catching performances of penaeid trawls (but see Broadhurst *et al*., 2012; 2013b). The main aim of this chapter was to address this shortfall by quantifying the catches and fuel efficiency (measured as least drag) associated with three conventional otter-board designs and the batwing (with its relatively less bottom contact) in one Australian fishery targeting school prawns, *Metapenaeus macleayi* (Haswell). A secondary aim was to use an approach involving removing the trawls and just towing the otter boards (separated by wire stays) to quantify their contribution towards total system drag for the tested trawls, so the benefits of future refinements to otter-board design and their AOAs can be established.

Materials and methods

Three experiments were completed in the Clarence River, New South Wales, Australia, during May 2013 using a local penaeid trawler (10 m and 89-kw) fishing in ∼4–18 m water-depth across mud and sand substrate. The trawler had 8-mm diameter (Ø) stainless warps and 40-m bridles (6-mm Ø stainless wire) on a double-drum, hydraulic split winch. The trawler was also equipped with: a fuel monitor (Floscan series 9000); global positioning system (GPS; Lowrance); hull-mounted sum log (EchoPilot, Bronze Log+), warp-attachable load cells and associated data logger (Amalgamated Instrument Company; model nos PA6139 and TP4); and a portable acoustic, trawl-monitoring system with paired wing-end distance sensors (Notus Trawlmaster System; Model no. TM800ET;

see Broadhurst *et al*., 2013a for details). All monitoring equipment was calibrated prior to starting the experiments.

Trawls and otter boards tested

Four trawls were constructed—two identical replicates of two similar designs (Figure 4. 1). The first two trawls (termed A and B) were conventionally mandated designs for the fishery, and comprised a mean stretched mesh opening (SMO) ± SE of 41.43 ± 0.11 mm (n = 20 meshes in each trawl) and 1.2-mm Ø twine, with a side taper of 1N3B and were used in experiment 1 (Figure 4. 1). Owing to the small sizes of penaeids encountered (see Results), the third and fourth trawls (labelled C and D) used in experiment 2 were made from smaller 31.61 ± 0.08 mm SMO (n = 20 meshes in each trawl) and 0.8 mm Ø twine, and with a side taper of 1N5B (Figure 4. 1). All four trawls were rigged with identical Nordmøre-grids and square-mesh codends made from 27.37 ± 0.10-mm SMO (n = 20 meshes in each trawl) polyamide (PA) mesh hung on the bar and had 2.89-m sweep wires (6-mm Ø wire) attached at their wing ends, terminating in snap clips to facilitate attachment to the otter boards.

Four otter-board pairs were tested, all with 100 mm base plates (Figure 4. 2). The first otter board represented a standard design used nationally and internationally, and comprised a mild-steel frame with marine-grade plywood inserts and was termed the 'flat-rectangular' (52.5 kg, 1.39 × 0.61 m, solid area of 0.77m^2; Figure 4. 2a). The second design ('kilfoil') was constructed entirely from galvanised mild steel and had three 270 mm-wide cambered vertical foils in a rectangular frame (63.0 kg, 1.25 × 0.63 m, solid area of 0.58 m^2; Figure 4. 2b), while the third ('cambered') had a single, cambered foil over its entire length and was made from stainless-steel plate (53.0 kg, 1.08 × 0.73 m, 0.79 m^2; Figure 4. 2c).

The fourth design was the batwing and comprised a main sled made from mild and stainless steel, and a polyurethane (PU) sail set on a stainless-steel boom and mast (60.7 kg, 1.12 × 1.23 m, 0.74 m^2) configured to remain at a 20° AOA (Figure 4. 2d). The batwing foil was designed to act like an independent kite with a single longitudinal connection to the trawl system via a heavy main sled made from a combination of mild and stainless steel (Figure 4. 2d). The batwing was configured so that the heavy sled baseplate was aligned to the tow direction, while the sail had a stable AOA and rode on a polyurethane flap designed to pass lightly over the seabed on a layer of pressurised water (similar in concept to the skirt on a hovercraft).

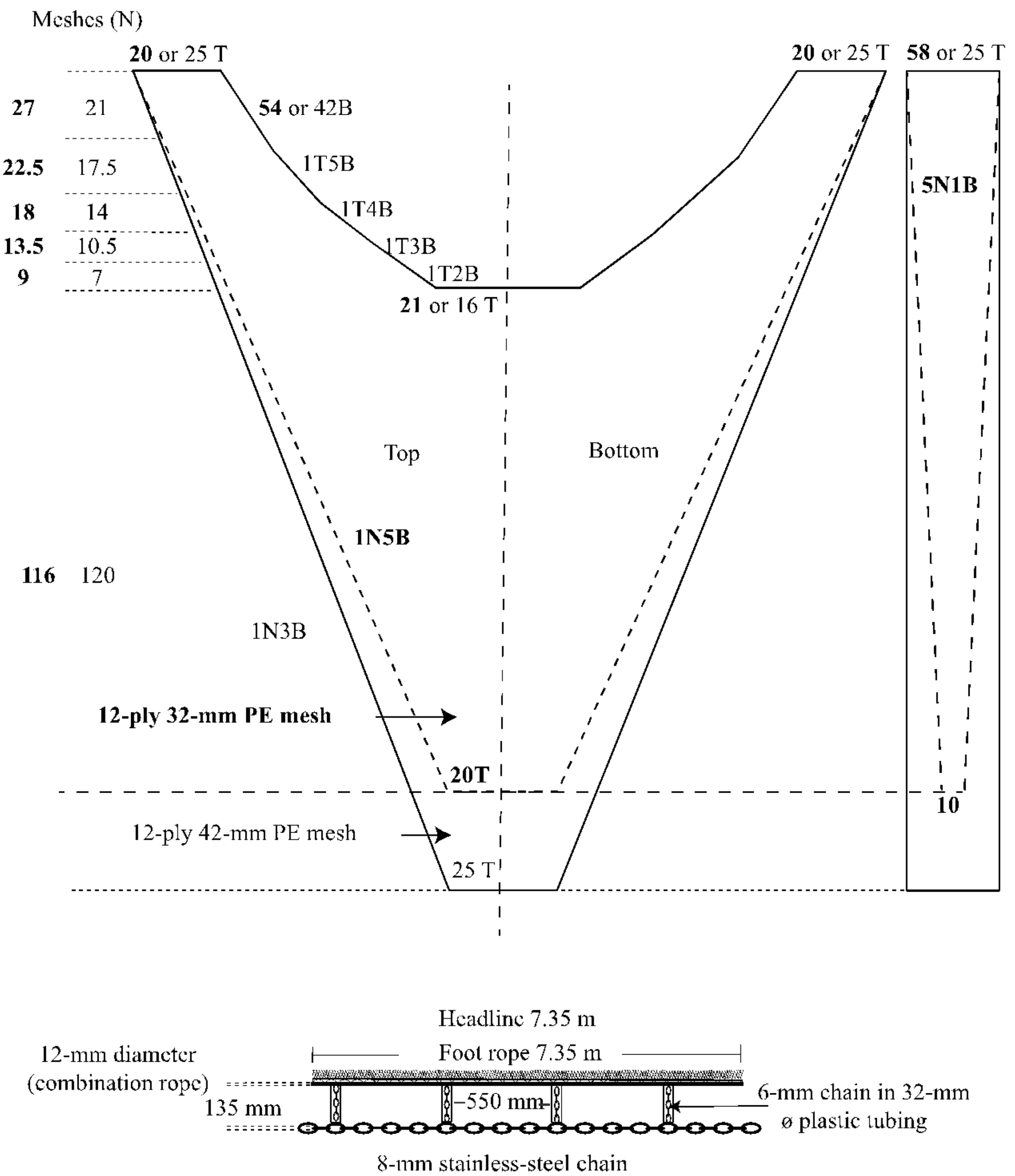

Figure 4. 1. Plans of the 41-and 32-mm trawls used in the study. N, normal; T, transversals; B, Bars; and Ø, diameter PE, polyethylene (information in bold is specific to the 32-mm trawl).

To ensure the same trawl wing-end height during fishing, vertical upper sweep wire attachment bars were welded to the tops of the flat-rectangular and kilfoil designs to match the heights of the cambered and batwing otter boards (Figure 4. 2). All otter boards were rigged at their industry-standard AOAs, and to achieve the same trawl wing-end spreads (see Results).

Experiment 1−four pairs of otter boards with trawls

In the first experiment, the four otter boards were tested against each other in paired comparisons. On each fishing day, one of the six possible otter-board combinations was attached to each side of the vessel. The 41-mm trawls (A and B) and sweep wires were clipped to the otter boards, while the Notus paired sensors were attached to the trawl wing ends. After two replicate deployments, the trawl-monitoring equipment (Notus sensors and load cells) were swapped from side-to-side, but the trawls remained. After four replicate deployments, both the trawls and the trawl-monitoring equipment were swapped from side-to-side. After six deployments, just the trawl-monitoring equipment was swapped again. In total, each of the four otter-board pairs were deployed across three alternate replicate days, with eight replicate 30-min deployments for each treatment on each day (providing a total of 24 deployments).

Experiment 2−two pairs of otter boards with trawls

To obtain more data over a broader range of conditions (and especially longer tow durations more representative of conventional operations), just the flat-rectangular and batwing otter boards were compared. On each of four days, pairs of the two otter boards were alternately attached to each side of the vessel, and clipped to the sweep wires attached to the 31-mm trawls. The smaller-mesh trawls were used to remove the possibility that confounding distortion of the trawls (particularly in the side panels) caused by the strain-equalizing mechanism of the batwing otter boards allowed small *M. macleayi* to escape (see Results and Discussion). The trawl monitoring equipment was randomly allocated to one side of the vessel on each day. Five 50-min deployments were completed on each day (i.e. a total of 20 deployments for each otter board), swapping the trawls from side-to-side after the third deployment.

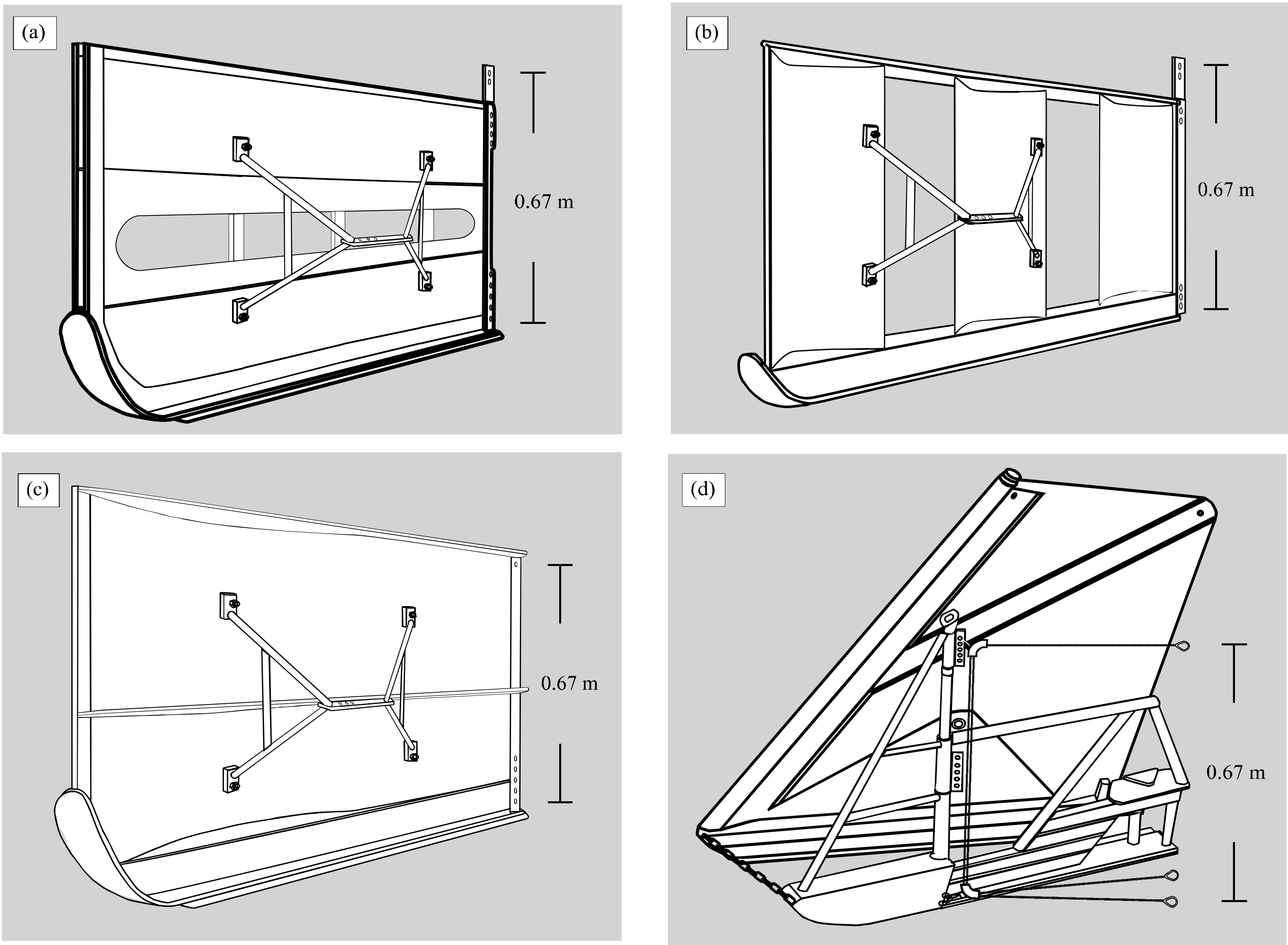

Figure 4. 2. Three dimensional representation of a) flat rectangular, b) kilfoil, c) cambered and d) batwing otter boards. The 0.67 m represents the upper and lower sweep-wire attachment points.

Experiment 3−two pairs of otter boards without trawls

In experiment 3, the flat-rectangular and batwing otter boards were again tested against each other as for experiment 2, but with the trawls removed to obtain drag estimates for the otter boards only. To limit separation of the otter boards and fix the AOA, two lengths of 3-m stainless steel wire (6-mm Ø) were secured between the upper and lower net attachment points on each otter board pair and a third wire (3.5 m) was connected between each otter-board pair at the warp connection points (Figure 4. 3). The trawl monitoring equipment was alternately allocated to one side of the vessel on each day (with the Notus paired sensors secured to the outside posterior surface of each otter board; Figure 4. 3) and between 8 and 12 replicate deployments completed over four days (total n = 40).

Data collected and statistical analyses

In all three experiments, the technical data collected describing the operational procedures during each deployment included the: (i) drag (kgf) of each gear configuration; (ii) total distance the gears were towed (otter boards on and off the bottom—obtained from the plotter and trawl-monitoring system); (iii) speed over the ground (SOG) and through the water (STW; both in m s^{-1}), (iv) water depth (m), (v) distance of the gear configurations behind the vessel, and (vi) wing-end (experiments 1 and 2) or otter-board (experiment 3) spreads (m). All electronic data were recorded at 60-s intervals. For experiments 1 and 2, otter-board AOA was estimated using the otter-board orientation model of Sterling (2000) with inputs of wing-end spread (for each deployment) and used to calculate otter-board span (contact) on the substrate (by multiplying the otter-board length by the sine of the AOA) and ultimately, the effective total bottom contact (average wing-end spread + otter-board lateral base-plate contact).

At the end of each deployment in experiments 1 and 2, all catches were separated by codend, with the total weights of *M. macleayi* and bycatch collected along with the numbers of each bycatch species. Total lengths (TL to the nearest 0.5 mm) of the most abundant teleosts were also collected. A random sample of ~500 g of *M. macleayi* was collected and a subsample (~100) measured (carapace length–CL in mm) in the laboratory. These data were used to estimate the total numbers caught and mean CL during each deployment.

The technical and biological data were separately analysed within experiments using linear mixed models (LMMs), with some standardised prior to analyses. Numbers and weights were analysed as log-transformed data, after being standardised to ha^{-1} trawled calculated using the footrope contact (average wing-end spread × distance trawled) and, additionally where these were significant for *M. macleayi*, the effective total-system contact (i.e. (wing-end spread + span of otter-board contact) × the distance trawled) for fishing. The latter was done to test the hypothesis that otter-board contact span explained some of the variability in *M. macleayi* catches (see Results), and did not include the batwing sleds, because these were outside the effective herding path of the trawl (Broadhurst *et al*., 2012). All other data, including the mean CL of *M. macleayi* per deployment, drag, wing-end spread, SOG, STW and distance trawled were analysed in their raw form.

All models included 'otter-board pair' as a fixed effect while, where appropriate (depending on the experiment), the random effects included 'trawls', 'trawl sides', 'otter-board sides' and 'days' and the interaction between 'deployments' and days. For the LMMs assessing drag and spread, additional random terms involved load cells and the paired Notus sensors, respectively while additional covariates included SOG, 'current' (calculated as the speed of the water in the direction of travel and defined as SOG–STW), distance aft of the trawl configuration from the vessel and fishing depth. All models were fitted using the lmer function from the lme4 package in R 2.15.3 (The R Project for Statistical Computing; http://www.r-project.org/) and the significance of trawl design was determined using a likelihood ratio test (LRT). The LRT was used to compare model log-likelihoods and test whether any differences were statistically significant (Rice, 2006). In experiment 1, where the levels of otter-board pair exceeded two, significant differences were explored using the Benjamini-Hochberg-Yekutieli procedure to control the false discovery rate (FDR; Benjamini and Yekutieli, 2001). The FDR is the expected proportion of false positive discoveries between all of the rejected hypotheses.

Relevant back-transformed predicted means from the LMMs were used to calculate relative fuel consumptions associated with towing the trawls and otter boards in experiments 1 and 2. Specifically, assuming that for any given towing speed, the concomitant fuel usage was proportional to the drag, it is possible to determine relative fuel consumption rate (L h^{-1}) between each side using the predicted mean drags as determined by the repeated load-cell measurements. Fuel consumption was standardised to ha^{-1} trawled (i.e. intensity) and kg^{-1} of *M. macleayi* caught for each otter-board configuration by comparing the predicted fuel consumption rate with predicted mean wing-end spread (the rate at which area was being swept for a given trawl speed), and the predicted absolute mean *M. macleayi* catches (derived by fitting the same model above to the unstandardised log-transformed data) from the respective LMMs.

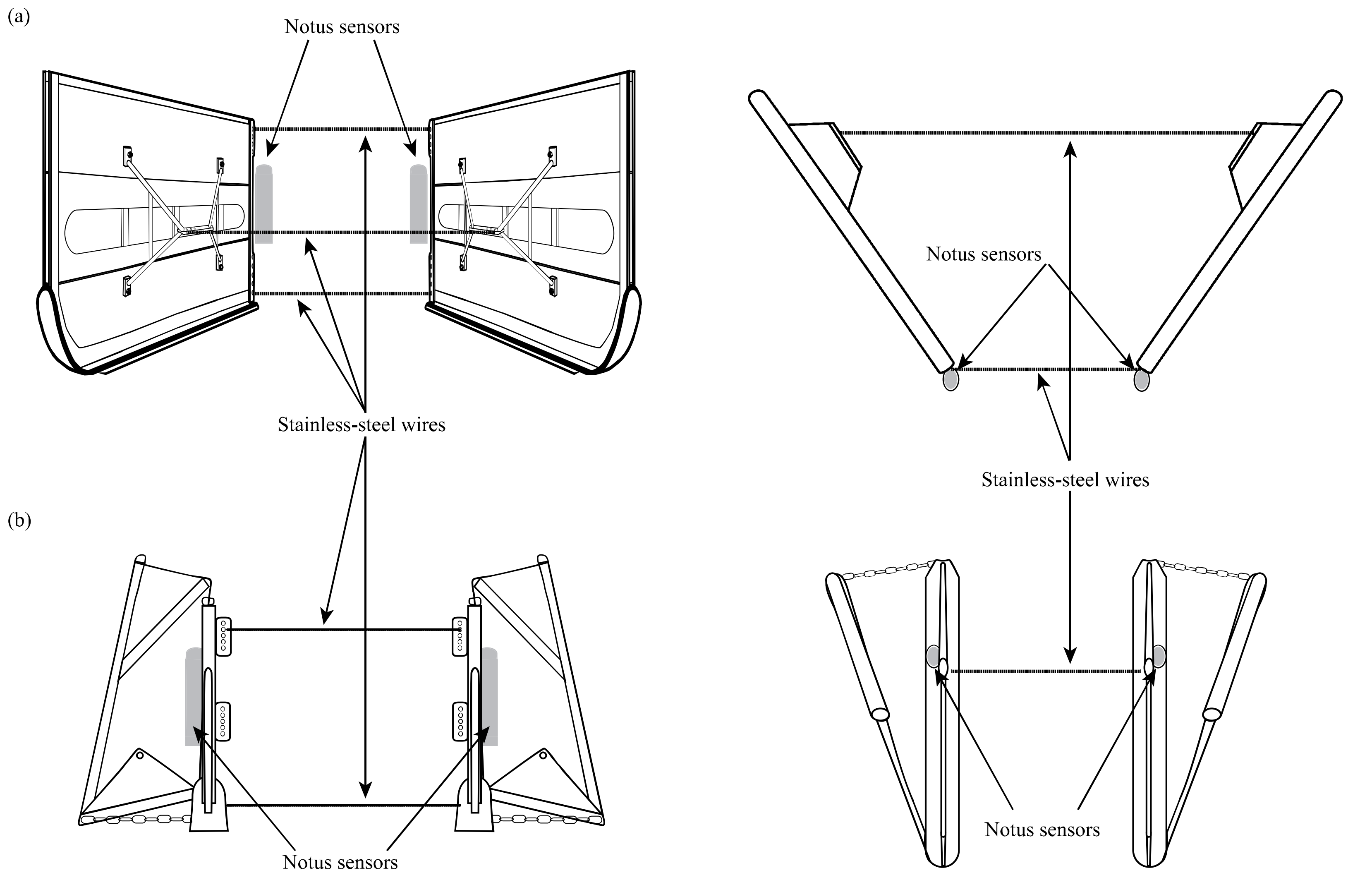

Figure 4. 3. Front and top views of the (a) flat-rectangular and (b) batwing otter boards rigged without a trawl in experiment 3.

Table 4. 1. Scientific and common names and numbers of organisms caught during experiments (Exp) 1 and 2. –, not present in catches.

Family	Scientific name	Common name	Total numbers	
			Exp. 1	Exp. 2
Crustaceans				
Palaemonidae	*Macrobrachium novaehollandiae*	Freshwater prawn	3	-
Penaeidae	*Metapenaeus macleayi*	School prawn[1]	182,568	164,424
	Penaeus monodon	Tiger prawn[1]	1	-
Teleosts				
Ambassidae	*Ambassis jacksoniensis*	Port Jackson glassfish	3	5
	Ambassis marianus	Ramsey's perchlet	11	53
Anguillidae	*Anguilla reinhardtii*	Long-finned eel[1]	8	3
Ariidae	*Arius graeffei*	Forktail catfish[1]	728	86
Apogonidae	*Siphamia roseigaster*	Pink-breasted siphonfish	–	3
Carangidae	*Pseudocaranx dentex*	Silver trevally[1]	–	1
Clupeidae	*Herklotsichthys castelnaui*	Southern herring	275	138
	Hyperlophus vittatus	Whitebait	7	4
Engraulidae	*Engraulis australis*	Australian anchovy	-	2
Gerreidae	*Gerres subfasciatus*	Silver biddy	3	27
Megalopidae	*Megalops cyprinoides*	Oxeye herring	–	3
Monodactylidae	*Monodactylus argenteus*	Diamond fish	6	40
Mugilidae	*Liza argentea*	Flat-tail mullet[1]	–	1
Paralichthyidae	*Pseudorhombus arsius*	Largetooth flounder	–	4
Platycephalidae	*Platycephalus fuscus*	Dusky flathead[1]	1	2
Plotosidae	*Euristhmus lepturus*	Longtail catfish	4	3
Pomatomidae	*Pomatomus saltatrix*	Tailor[1]	12	11
Scatophagidae	*Selenotoca multifasciata*	Old maid	5	4
Sciaenidae	*Argyrosomus japonicus*	Mulloway[1]	184	63
Soleidae	*Synclidopus macleayanus*	Narrow banded sole	81	13
Sparidae	*Acanthopagrus australis*	Yellowfin bream[1]	119	750
	Rhabdosargus sarba	Tarwhine	–	1
Tetrarogidae	*Notesthes robusta*	Bullrout	33	76

[1]economically important

Results

Metapenaeus macleayi comprised 99% of the total catches in experiments 1 and 2 (Table 4. 1). The minimal bycatch included 25 species, but was dominated by forktail catfish, *Arius graeffei* (Kner and Steindachner); 8.0–13.5 cm TL), southern herring, *Herklotsichthys castelnaui* (Ogilby); 7.0–16.0 cm TL) and mulloway, *Argyrosomus japonicas* (Temminck and Schlegel); 4.5–20.5 cm TL) in experiment 1 (80% of the total catch) and yellowfin bream, *Acanthopagrus australis* (Owen); 6.5–23.5 cm TL) and *H. castelnaui* (7.0–15.5 cm TL) in experiment 2 (64%) (Table 4. 1).

Experiment 1−four pairs of otter boards with trawls

The four otter-board and trawl configurations were towed at (mean ± SE) SOG of 1.24 ± 0.01 m s^{-1} and STWs of 1.43 ± 0.08 m s^{-1}. There was no significant difference in the wing-end spreads of the trawls rigged among otter-board pairs, nor distance trawled (LMM, $p > 0.05$; Tables 4. 2 and 4. 3), but otter-board AOAs, total bottom contact and drag were all significantly different (LMMs, $p < 0.01$; Tables 4. 2 and 4. 3). Specifically, while the batwing maintained a 20° AOA, the kilfoil (30.58 ± 0.04°), flat-rectangular (32.83 ± 0.04°) and cambered (38.62 ± 0.04°) designs were spread at significantly (and incrementally) greater AOAs (FDR, $p < 0.05$; Tables 4. 2 and 4. 3). However, the AOAs did not significantly affect the total bottom contact (because the different otter-board lengths offset any relative reductions) among the conventional configurations (FDR, $p > 0.05$; Tables 4. 2 and 4. 3), but all three had significantly greater total bottom contacts than the batwing configuration (up to 1.24 times more; FDR, $p < 0.05$; Table 4. 3). For individual otter boards (from the four designs), a combination of their AOA and length altered (by up to 66%) their projected surface area to between ~0.25 and ~0.48 m^2.

The LMM for drag included the fixed effects of otter-board pair, SOG and current, with the former two being significant ($p < 0.05$). To facilitate presentation, the predicated mean drags were calculated at the centred value of SOG (i.e. drag at average SOGs) and for zero current (Table 4. 3). Compared to all three conventional systems, the batwing configuration had significantly less drag (predicted mean reduced by between 14.00 and 18.34%). Further, compared to the kilfoil and cambered otter-board configurations (which had the same drag; FDR, $p > 0.05$; Table 4. 3), there was less drag associated with the flat-rectangular configuration (by 5%; FDR, $p < 0.05$; Table 4. 3). The fuel rate varied between ~5.00 and ~6.13 L h^{-1} while fuel intensity was between ~2.20 and ~2.68 L ha^{-1}, with the batwing otter boards requiring the least fuel to tow (Table 4. 3).

For the biological variables, significant differences were limited to *M. macleayi* catches, with the most consistent difference being that the batwing configuration retained significantly fewer individuals ha^{-1} of footrope contact (by both weight and number) than the conventional configurations (LMM, $p < 0.05$, Table 4. 2, Figure 4. 4a and b). Standardizing catches to ha^{-1} of total-system contact (to incorporate the otter-board span on the bottom) eliminated some of the significant differences among the conventional and batwing configurations, but not all (Figure 4. 4a and b). In particular, the cambered otter-board configuration retained significantly more *M. macleayi* by weight (by between 11 and 33%) than the other designs, and also at a significantly smaller mean size (15.22 ± 0.11 mm CL) than the batwing configuration (15.52 ± 0.11 mm CL) (FDR, $p < 0.05$; Figure 4. 4a). Although not significant, the cambered otter-board configuration also caught a smaller mean CL of *M. macleayi* than the kilfoil (15.27 ± 0.11 mm CL) and flat-rectangular (15.34 ± 0.11 mm CL) (FDR, $p > 0.05$). No significant differences were detected for catches of fish (LMM, $p > 0.05$; Table 4. 2, Figure 4. 4c−g).

Table 4. 2. Summaries of likelihood ratio test (LRT) statistics from linear mixed models assessing the importance of the fixed effect of otter-board pairs in experiments (exp) 1 (flat-rectangular, kilfoil, cambered and batwing attached to identical 41-mm mesh trawls), 2 (flat-rectangular and batwing attached to identical 32-mm mesh trawls) and 3 (flat-rectangular and batwing with no trawls) in explaining variability among key technical and, where relevant, biological responses. Numbers and weights were analysed as log-transformed data, after being standardised to ha^{-1} trawled calculated using the footrope contact (average wing-end spread × distance trawled) and, additionally where these were significant for the school prawns, *Metapenaeus macleayi*, the total-system contact ((i.e. wing-end spread + span of otter-board contact) × the distance trawled). −, not present in sufficient numbers. NA, not applicable for analyses; †, no LRT available because the batwing otter board maintained a constant 20^{o} angle of attack (AOA). Owing to a significant interaction with SOG, no main effect of otter board was presented for drag in experiments 2 and 3 (see Table 4. 3).

	LRT		
Technical variables	Exp 1	Exp 2	Exp 3
Wing-end (exp 1 and 2) or otter board (exp 3) spread	1.49	0.04	9.27**
Distance trawled	0.87	1.03	1.07
Otter-board AOA	33.46***	†***	†***
Total bottom contact	41.27***	7.81**	NA
Drag	9.64*	NA	NA
Biological variables			
Wt of school prawns *Metapenaeus macleayi* ha^{-1} of footrope contact	18.89***	0.76	NA
Wt of *M. macleayi* ha^{-1} of total-system contact	9.13*	NA	NA
No. of *M. macleayi* ha^{-1} of footrope contact	12.78**	1.13	NA
No. of *M. macleayi* ha^{-1} of total-system contact	6.02	NA	NA
CL of *M. macleayi*	8.19*	2.54	NA
Wt of total bycatch ha^{-1} of footrope contact	0.72	0.10	NA
No. of total bycatch ha^{-1} of footrope contact	1.00	0.22	NA
No. of yellowfin bream *Acanthopagrus australis* ha^{-1} of footrope contact	–	2.87	NA
No. of forktail catfish *Arius graeffei* ha^{-1} of footrope contact	3.36	0.41	NA
No. of southern herring *Herklotsichthys castelnaui* ha^{-1} of footrope contact	4.47	0.42	NA
No. of mulloway *Argyrosomus japonicus* ha^{-1} of footrope contact	0.69	–	NA

*$p < 0.05$
**$p < 0.01$
***$p < 0.001$

Table 4. 3. Summary of predicted mean ±SE wing-end spreads or footrope contact (m), otter-board angles of attack (AOA), otter-board projected area (m^2), total bottom (footrope + otter-board base-plate linear span) contact (m), drags (kgf) and subsequent estimated fuel rates and intensities for four pairs of otter boards (flat-rectangular, kilfoil, cambered and batwing otter boards) attached to identical 41-mm mesh trawls in experiment 1 and two pairs of otter boards (flat-rectangular and batwing) attached to identical 32-mm mesh trawls in experiment 2, and spread, AOA and drags for the pairs of the flat-rectangular and batwing otter boards tested without trawls in experiment 3. Mean predicted drags were derived with a centred value of speed over the ground and with zero current. The predicted areas (of individual otter boards) were derived from the percentage of overall surface area when correcting for AOA. Dissimilar superscript letters within experiments indicate significant differences detected in false-discovery-rate pairwise comparisons (experiment 1) or linear mixed models (experiments 2 and 3) ($P < 0.05$). −, Not applicable.

	Otter board pairs			
	Flat-rectangular	Kilfoil	Cambered	Batwing
Experiment 1− four otter-board pairs with 41-mm mesh trawls				
Wing-end spread or footrope contact (m)	5.08 (0.06)^{A}	5.17 (0.06)^{A}	5.13 (0.06)^{A}	5.10 (0.06)^{A}
Otter-board AOA (^{o})	32.83 (0.40)^{C}	30.58 (0.40)^{B}	38.62 (0.40)^{D}	20 (0.00)^{A}
Otter-board projected area (m^2)	0.41	0.29	0.48	0.25
Total bottom contact (m)	6.58 (0.07)^{B}	6.44 (0.07)^{B}	6.47 (0.07)^{B}	5.30 (0.07)^{A}
Drag (kgf)	251.57 (2.45)^{B}	264.94 (3.18)^{C}	264.46 (2.46)^{C}	216.33 (3.18)^{A}
Fuel rate (L h^{-1})	5.82	6.13	6.12	5.00
Fuel intensity (L ha^{-1})	2.57	2.66	2.68	2.20
Experiment 2− two otter-board pairs with 32-mm mesh trawls				
Wing-end spread (m)	5.17 (0.12)^{A}	−	−	5.12 (0.12)^{A}
Otter-board AOA (^{o})	33.71 (0.98)^{B}	−	−	20 (00)^{A}
Otter-board projected area (m^2)	0.42	−	−	0.25
Total bottom contact (m)	6.73 (0.15)^{B}	−	−	5.32 (0.15)^{A}
Drag (kgf)	268.14 (2.08)^{B}	−	−	227.93 (2.01)^{A}
Fuel rate (L h^{-1})	6.21	−	−	5.28
Fuel intensity (L ha^{-1})	2.33	−	−	2.00
Experiment 3− two otter-board pairs without trawls				
Otter-board spread (m)	2.59 (0.10)^{A}	−	−	2.92 (0.10)^{B}
Otter-board AOA (^{o})	32.59 (2.13)^{B}	−	−	20 (00)^{A}
Drag (kgf)	158.65 (3.79)^{B}	−	−	116.74 (3.77)^{A}

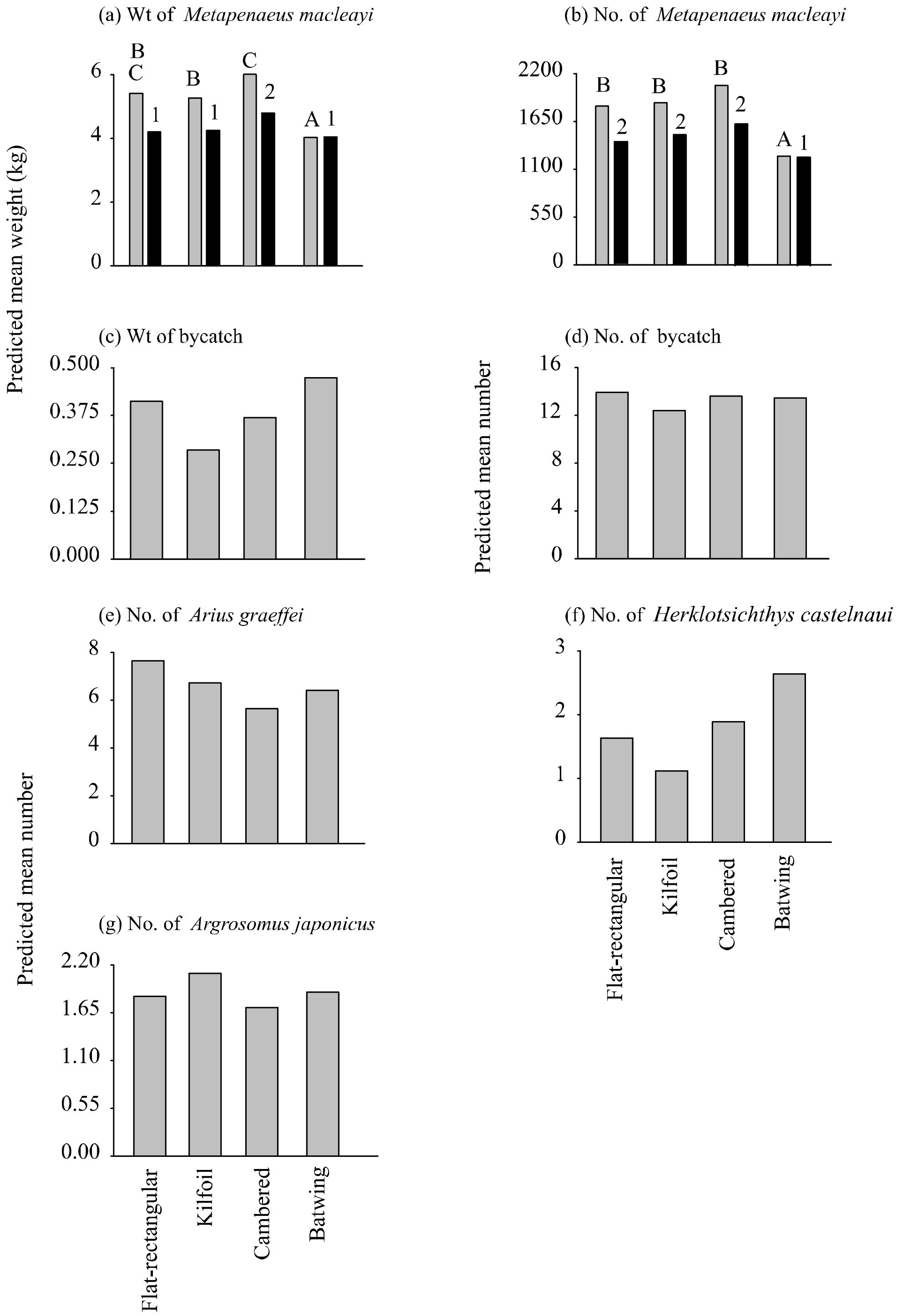

Figure 4. 4. Differences in predicted mean catches ha^{-1} trawled of footrope contact (grey histograms) and, where relevant, total-system contact (black histograms) between identical 41-mm mesh trawls spread with pairs of flat-rectangular, kilfoil, cambered and batwing otter boards for the (a) weights and (b) numbers of school prawns (*Metapenaeus macleayi*), (c) weights and (d) numbers of bycatch and numbers of (e) forktail catfish, *Arius graeffei*, (f) southern herring, *Herklotsichthys castelnaui* and (g) mulloway, *Argyrosomus japonicus*. Dissimilar letters and numbers above the histograms indicate significant differences detected in false-discovery-rate pairwise comparisons ($p < 0.05$).

Experiment 2−two pairs of otter boards with trawls

The flat-rectangular and batwing otter-board configurations were towed at mean ± SE SOGs and STWs of 1.29 ± 0.01 and 1.28 ± 0.01 m s^{-1}. There was no significant difference in the wing-end spread of the 31-mm mesh trawls rigged between otter-board pairs, nor the distance trawled (LMM, $p > 0.05$; Tables 4. 2 and 4. 3), however like for experiment 1, the AOA, total-bottom contact and drag were all significantly different (LMMs, $p < 0.001$; Tables 4. 2 and 4. 3). The differences between otter-board pairs for AOA, total bottom contact and projected surface area followed those for experiment 1 (Tables 4. 2 and 4. 3). For drag, the parsimonious LMM included a significant interaction between gear and SOG and a significant main effect of current ($p < 0.01$). The predicated mean drags for the two configurations are presented at the centred value of SOG (i.e. drag at average SOGs) and for zero current; under which criteria the batwing configuration had ~15% less drag than the flat-rectangular configuration (Table 4. 3). The fuel rate equated to ~5.28 and ~6.21 L h^{-1} while fuel intensity was ~2.00 and ~2.33 L ha^{-1} for the batwing and flat-rectangular otter boards, respectively (Table 4. 3).

In terms of catches ha^{-1} trawled of footrope contact, no significant differences were detected between otter-board configurations for any of the variables, although the predicted mean weights and numbers of *M. macleayi* were 5.07 and 7.67% lower for the batwing configuration (LMM, $p > 0.05$, Table 4. 2 and 4. 4). Further, although there were few data (n = 104), the LRT *p*-value for *A. australis* catches was 0.09, with a corresponding 1.4 times mean increase in the numbers retained in the batwing configuration (Table 4. 2 and 4. 4).

Experiment 3−two otter boards without trawls

Substituting a trawl with wire stays between the paired flat-rectangular and batwing otter boards presented few logistical problems, with both configurations towed at mean ± SE SOGs and STWs of 1.31 ± 0.01 and 1.69 ± 0.06 m s^{-1}. Compared to the flat-rectangular otter-board pair, the batwing pair were spread significantly wider (11% difference in predicted means) and at a lower AOA (20 ± 00 vs 32.59 ± 2.13°; LMM, $p < 0.01$; Tables 4. 2 and 4. 3). The parsimonious LMM for drag comprised a significant interaction between otter-board configuration and SOG, and a main effect of current ($p < 0.01$; Table 4. 3). At average SOG and for zero current, the predicated mean drag of the batwing pair was 116.75 ± 3.77 kg, or 26% less than that for the flat-rectangular otter board (158.65 ± 3.79 kg; Table 4. 3).

Table 4. 4. Differences in predicted mean catch variables ha^{-1} trawled of footrope contact (average wing-end spread × distance trawled) between identical 32-mm mesh trawls spread with pairs of flat-rectangular and batwing otter boards.

Variables	Batwing	Flat-rectangular
Wt of school prawns *Metapenaeus macleayi* ha^{-1} trawled	5.43	5.61
No. of *M. macleayi* ha^{-1} trawled	2044.76	2209.02
Wt of total bycatch ha^{-1} trawled	0.46	0.48
No. of total bycatch ha^{-1} trawled	16.00	17.57
No. of yellowfin bream *Acanthopagrus australis* ha^{-1} trawled	9.61	13.37
No. of forktail catfish *Arius graeffei* ha^{-1} trawled	0.86	0.76
No. of southern herring *Herklotsichthys castelnaui* ha^{-1} trawled	1.74	1.43

Discussion

Compared to the conventional otter boards, the batwing consistently demonstrated a superior engineering performance, ultimately manifesting as maintenance of sufficient trawl SR with the least drag and therefore the lowest fuel intensity and rate (up to 2.26 L h^{-1} or 0.96 L ha^{-1} lower, for double rig in the tested fishery). This result can be attributed to the two key aspects of the batwing's design: (i) a baseplate aligned with the tow direction, which eliminated the shearing force on the bottom; and (ii) the hinged, hydrodynamic wing with a low AOA (20°), which reduced hydrodynamic drag (Sterling and Eayrs, 2010).

The inherent, consistent engineering benefits of the batwing are quite important, given that fuel can represent a large proportion (up to 30%) of a trawler's operating costs (e.g. Thomas *et al.*, 2010). Any reduction in the overall trawl system drag will help to alleviate some of the fuel used during trawling; of which conventional otter boards typically represent anywhere from 30% in single rig configurations (Sterling and Eayrs, 2010) to the 56% estimated here in experiment 3 (by comparing with data from experiment 2). Based on the data for the studied fishery, replacing any of the conventional otter-board pairs with the batwing would reduce fuel while trawling by between 16 and 22%, which would equate to between ~$A 2−3 K per fishing season.

While there are numerous conventional otter-board designs, often incorporating complex foil and camber arrangements, which might similarly reduce hydrodynamic drag and improve efficiency, many fishers still use basic designs like the flat-rectangular (Patterson and Watts, 1985; Sterling, 2000). The popularity of the flat-rectangular otter board among local fishers is supported by the results from experiment 1, with it having the least drag (by ~5%) of the conventional designs. Until recently, in many fisheries, the flat-rectangular otter board was among the most common designs operated (e.g. nearly 100% usage in Australian penaeid fisheries until the mid-1980s; Sterling and Eayrs, 2010); reflecting a combination of its simple, easily constructed and maintained design, and comparative efficiency to many contemporary otter boards when operated at 30–40° AOA (e.g. Patterson and Watts, 1985; Seafish *et al.*, 1993).

While it is imperative that otter boards are appropriately rigged to maximise hydrodynamic performance (Sterling and Eayrs, 2010), their overall length is also important in terms of habitat impacts. For example, the cambered otter boards tested in experiment 1 had high substrate contact (~62% of their length at the average 38.62° AOA). The batwing offers a real solution to minimising habitat impacts by having its main substrate contact (the sled) aligned in the direction of towing. Specifically, a conventional otter board 1.12 m long (the same as the batwing) operating at a typical AOA of 35–40° will have ~0.64–0.72 m of lateral contact compared to the ~0.1 m wide baseplate (assuming minimal habitat disturbance of the 'flap') for the batwing. Using an otter board with a fixed (or low) AOA would also reduce system contact, but as demonstrated in experiment 1, a combination of AOA and otter-board length needs to be considered, because a long otter board at a shallow AOA could still contact more of the sea bed than a short design at a more acute AOA.

While reducing total system contact via otter-board configurations may help to mitigate habitat impacts, a concomitant effect could be reduced catches of penaeids (Broadhurst *et al*., 2012). The cambered otter boards currently are the preferred design in the Clarence River fishery—primarily because they are perceived to catch more *M. macleayi* (supported by the results here) than other contemporary designs, which may in part result from their substantial ground contact. However, it is also possible that their large projected surface area (in the direction of the tow) is important. Specifically, this design had more projected area (~18–95% or ~0.07–0.24 m^2 after adjusting for AOA) than the other otter-board designs. Even a small increase in projected area may have directed more *M. macleayi* towards the trawl mouth. Such effects might also explain why, despite the lower substrate contact, the batwing maintained catches of *M. macleayi* in experiment 2. Specifically, the large sail and flap might have deflected some individuals close to the substrate into the trawls.

While the cambered otter boards improved *M. macleayi* catches, this was somewhat offset by their lower fuel efficiency than the flat-rectangular design. Such a result supports the concept that before implementing new otter-board designs (or other modifications), an holistic approach is necessary that allows profit margins to be maintained while increasing environmental efficiency. A comprehensive set of experiments (e.g. testing with a variety of trawl designs in different fisheries) is required; otherwise fishers are unlikely to commit to the continued use of new designs over the long term (Jennings and Revill, 2007).

It is also clear that introducing any technical modification requires careful adjustment and refinement across a broad range of conditions as possible prior to use. For example, in experiment 1, the batwing was associated with significantly lower catches of *M. macleayi* than the conventional otter-board designs. I attributed this result to the more dynamic net attachment points—movable wire cables instead of fixed points on conventional designs—which may have permitted the trawl wing to operate slightly higher in the water column, allowing sustained lateral opening of the meshes down the sides of the trawl—thus increasing escape opportunities. Using the batwing and flat-rectangular boards with the smaller (32 mm) meshed trawls in experiment 2 negated these issues and resulted in catches not being significant different for the two otter board types. The importance of electronic monitoring equipment (e.g. Notus sensors and fuel meters) was reinforced by observing that changing to the smaller mesh trawl did not affect the relative differences in performance (e.g. wing-end spread, drag and fuel rates) between experiments.

The results from this study suggest that the batwing otter board has good potential for reducing fuel consumption while maintaining the catching performances of the assessed penaeid trawls. Using otter boards with minimal substrate contact (such as the batwing) will also potentially reduce damage to trawled areas (van Marlen *et al.*, 2010). While creating the definitive otter board may ultimately be difficult to achieve, I believe that to make significant improvements to overall trawl efficiency it may be more conducive to focus further research on an otter-board design that has already attained satisfactory engineering performance (e.g. the batwing) and work on improving its catching performance. The pair of batwings tested here would cost ~$A 3 K which is comparable to purchasing a pair of flat-rectangular otter boards and ~$A 2 K less than the cambered otter boards. Batwing maintenance is equivalent to other otter boards, which combined with their superior fuel efficiency, should facilitate quicker investment returns (i.e. within ~one season, depending on which otter-board design they are replacing).

Alternatively, it might be advantageous to investigate the possibility of modifying existing designs—perhaps to incorporate the key mechanisms of designs such as the batwing to improve engineering and/or catching performances. While not specifically tested, based on the results, an otter board with superior engineering performance will also likely have a lower AOA, which has concomitant potential for reducing habitat impacts (Sterling and Eayrs, 2008; van Marlen *et al.*, 2010).

Chapter 5: Relative benthic disturbances of conventional and novel otter boards

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Abstract

Reducing otter-board angle of attack (AOA) has been proposed for limiting the habitat impacts of demersal trawls, but there are few quantitative assessments. This chapter tested the hypothesis that a novel otter-board design, termed the ‘batwing’ (comprising a 0.1-m wide sled with an offset sail at 20^{o} AOA) would have relatively fewer bottom impacts than a conventional flat-rectangular otter board (35^{o} AOA, with a similar hydrodynamic spreading force). Pairs of each otter board were suspended beneath a purpose-built rig comprising a beam and posterior semi-pelagic collection net and repeatedly deployed across established trawl grounds in an Australian estuary. Compared to the conventional otter-boards, the batwings displaced significantly fewer empty shells, *Anadara trapezia*, (Deshayes) and *Spisula trigonella*, (Lamarck), by 89% and school prawns, *Metapenaeus macleayi* (Haswell), by up to 78%. These rates were similar to the difference in base-plate bottom contact (87%). Further, the batwing damaged proportionally fewer damaged shells, attributed to their displacement away from the board’s surface area. Other debris (lighter pieces of wood) and benthic fish, bridled gobies—*Arenigobius bifrenatus* (Kner), were not as greatly mobilised (i.e. reduced by 50 and 25%, respectively); possibly due to their position on or slightly off the bottom, and a similar influence of hydrodynamic displacement by the hydro-vane surface areas. Although the consequences of reducing otter-board bottom contact largely remain unknown, low AOA designs like the batwing may represent a practical option for fisheries where trawling is perceived to be hazardous to sensitive habitats.

Keywords: Batwing, habitats, hydrodynamic drag, impact, otter boards

Introduction

Demersal trawling occurs throughout the world's oceans and is believed to have originated in the mid-14th century with a design called the 'wondyrchoum'; essentially a precursor to modern beam trawls (Robinson, 1996; Kennelly and Broadhurst, 2002). Technology evolved to 'otter trawling' in the late 19th century, which involves the nets being horizontally spread by the relative flow of water (from forward motion of the gear) acting on hydro vanes (or 'otter boards') (Jones, 1992; Auster and Langton, 1999). Since the early 20th century, otter trawling has become established as the world's most widely-used mobile fishing gear and is considered a principal source of anthropogenic disturbances to benthic habitats (Jones, 1992; Auster and Langton, 1999; Collie *et al.*, 2000; Kaiser *et al.*, 2002).

Many concerns about habitat impacts associated with demersal otter trawls have focused on the otter boards, which leave discernible marks on the substrate, and in some cases lead to unwanted ecosystem impacts (Dayton *et al.*, 1995; Auster and Langton, 1999; Kaiser *et al.*, 2002). Substrate type (e.g. hard or soft) and its mobility will dictate the impact of otter boards and recovery times, whereby soft sediments (e.g. mud and sandy-mud) with a low level of natural disturbance, will be most affected and take longer to recover than harder substrates (e.g. sand) (DeAlteris *et al.*, 1999, 2000; Dernie *et al.*, 2003).

While otter-board impacts are a direct function of their weight and contact pressure (by necessity they have the greatest concentrated mass within demersal trawls), there are two other key factors that ultimately affect the substrate contact area. First is the height-to-length ratio, or aspect ratio of the foil, which determines the otter board's length for a given foil surface area (Patterson and Watts, 1985; Seafish *et al.*, 1993). Second is the operational angle of attack (AOA), which typically is between 30 and 45° (Patterson and Watts, 1985; Seafish *et al.*, 1993). Considering these two factors, an otter board's lateral span of seabed contact can be deduced from simple trigonometry to be the base-plate width, for an AOA of 0°, to a maximum of the base-plate length, for a hypothetical 90°AOA.

Many conventional demersal otter boards are flat and rectangular with a low aspect ratio to match their high AOA (>35°); which although not required to adequately spread the trawls during fishing (i.e. 30° is most effective, while ~20° is the most efficient), ensures their stability during deployment (Sterling and Eayrs, 2010). A novel, high-aspect otter-board design that achieves a consistent low AOA and has good stability is the 'batwing' (Sterling and Eayrs, 2008; McHugh *et al.*, 2015). The batwing foil—comprising a polyurethane (PU) sail set on a stainless-steel boom and mast—acts like an independent kite with a single longitudinal connection to the trawl system via a heavy main sled made from mild and stainless steel. The batwing is configured so that the sled base-plate aligns to the tow direction, while the sail has a consistent AOA (20^{o}) and rides on a PU 'flap' that passes lightly over the seabed on a layer of high pressure water for most of its length. Conceivably, because the batwing mostly contacts the seabed via its base-plate width (assuming the sail has minimal contact) it should evoke proportionally fewer habitat disturbances than conventional, low-aspect and high AOA otter boards.

Identifying component-specific effects on habitats are difficult when using a complete trawl configuration (i.e. otter boards, net, ground gear and associated components; Gilkinson *et al.*, 1998). One method is via in-situ observations (e.g. video and sonar imaging), although in some fisheries these are limited owing to low visibility and difficulties discerning trawl-mark longevity (existing or new) (Smith *et al.*, 2007). Furthermore, proper experimental procedures require observations (e.g. video and sonar) to be collected before, during and after planned experiments (Schwinghamer *et al.*, 1998); which can be a difficult task in established fisheries (Dayton *et al.*, 1995).

An alternative option involves assessing broad relative benthic disturbances among different otter boards in the same space and time, which can then be used as a proxy for determining the utility or otherwise of modified designs for conserving habitats. I follow this approach here using a purpose-built test rig comprising a posteriorly located collection net (analogous to a covered codend) to investigate the hypothesis of no differences in the relative substrate disturbances of conventional flat-rectangular and batwing otter boards. The rig was alternately deployed across flat (sandy-mud), previously trawled areas known to contain large areas of empty shell (*Anadara trapezia,* Deshayes and *Spisula trigonella,* Lamarck) and other macro debris, so that their abundances in the collection net and any inflicted damage could be used as relative indices of disturbance.

Materials and methods

The experiment was completed in Lake Wooloweyah (29° 26'S 153° 22'E; ~1–2 m depth), New South Wales, Australia during the Austral autumn, 2014 using a 10-m penaeid trawler (104 kw) configured with two independent hydraulic winches to tow double rig. The trawler had a global positioning system (GPS; Lowrance, HDS5) to record speed over the ground (SOG in m s^{-1}) (every 60 s). The experiment was done at the end of the fishing season and with no other vessels present on the trawled area.

Otter boards and the testing assembly

Two otter-board pairs were assessed; both with 0.1-m base-plates (Figures 5. 1 and 5. 2). The first otter board pair was termed the 'flat-rectangular' and represented a standard design used nationally and internationally, comprising a mild-steel frame with marine-grade plywood inserts (52.53 kg, 1.39 × 0.61 m, solid area of 0.77 m^2; Figure 5. 1a). The second pair was the 'batwing'; each with a main sled made from mild and stainless steel, and a polyurethane (PU) sail on a stainless-steel boom and mast (60.74 kg, 1.12 × 1.23 m, 0.74 m^2) at a 20^o AOA (Figures 5. 1b and 5. 2a).

Both otter-board pairs were deployed, one pair at a time on a purpose-built test rig comprising a 6-m beam secured at each end to sleds (1.07 × 0.76 × 0.1 m); inside which a 'collection net' (a design described by McHugh *et al.*, 2015 and made from 32- and 12-mm polyethylene mesh in the body and codend) was posteriorly attached (Figure 5. 2). The collection net had no ground gear. Rather, the lower frame line was attached 0.1 m above and inside the sled base-plates so that it could not contact (nor disturb) the substrate, nor collect any entrained material from the sled (Figure 5. 2). This lack of substrate contact was validated in earlier work, when the configuration was fished without the attached otter boards (Broadhurst *et al.*, 2015a).

The flat-rectangular and batwing otter boards were bolted at their conventional fishing orientations (35 and 0^o base-plate AOA, providing total lateral bottom contacts of 1.60 and 0.20 m, respectively) to independent aluminium frames that could be secured immediately below the beam and 1-m either side of the centre line, so that the base-plates were on the same plane as the sleds, and in front of the collection net (Figure 5. 2). The beam assembly was attached via a 7-m bridle to the towing warps on one side of the vessel, and a conventional otter trawl was operated on the other side (to balance the vessel during towing). On each fishing day, an otter-board pair was suspended below the beam and deployed for 10 min along independent tracks (Figure 5. 2). The otter-board pairs were alternately deployed among four days and also within two days, providing a total of 36 replicates of each.

Data collected and statistical analyses

Data collected during each deployment were restricted to the test rig and collection net and included: the total distance (m) trawled (rig on and off the bottom—obtained from the GPS); SOG (m s^{-1}); total catch weight; the numbers and weights of individual fauna; sizes of key species (carapace length−CL for penaeids and total length−TL for fish to the nearest 1 mm); and the weights of shells and other debris (mostly water-saturated wood). Estimates of faunal abundance were derived using a 500-g subsample of the total catch, processed in the laboratory. Empty shells were also classified as 'damaged' (i.e. broken pieces) or 'undamaged' (structurally complete).

Owing to difficulties in identifying penaeids to the species level, two groups were classified: individuals >5-mm CL (entirely school prawns, *Metapenaeus macleayi*, Haswell) and those <5-mm CL (some *M. macleayi*, but mostly glass shrimp, *Acetes* spp.), termed 'misc. Dendrobranchiata'.

All data were separately analysed in linear mixed models (LMMs), with some standardised prior to analyses. Catch numbers and weights were analysed as log-transformed data, after being standardised to 500-m^{-1} deployment (because of differences in the distance towed—see Results). All other data, including the mean CL of *M. macleayi* (>5-mm CL), ratio of damaged and undamaged shells, and deployment distance were analysed in their raw form.

All LMMs included 'otter-board pair' as a fixed effect, while 'days', 'deployments' and, where relevant, their interaction, were included as random terms. All models were fitted using ASReml (Gilmour *et al*., 2006) in the R software package (R Core Development Team, 2014). The null hypothesis of no difference between otter-boards was tested using a Wald *F*-test, which is a modification of the standard Wald test to provide better inference about fixed effects in mixed models. Specifically, the Wald *F*-test is derived by dividing the standard Wald test statistic by the denominator degrees-of-freedom following Kenward and Roger (1997).

Results

A total catch of 87.82 kg was retained in the collection net, comprising *M. macleayi* (3.97 kg), misc. Dendrobranchiata (6.29 kg), shells (50.28 kg), wooden debris (12.71 kg), blue blubber jellyfish, *Catostylus* spp. (9.71 kg) and teleosts (4.86 kg). The latter included 23 species, but five comprised 85% of the total (by number): southern herring, *Herklotsichthys castelnaui* (Ogilby) (38%); pink-breasted siphonfish, *Siphamia roseigaster* (Ramsay and Ogilby) (17%); whitebait, *Hyperlophus vittatus* (Castelnau) (15%); Australian anchovy, *Engraulis australis* (White) (11%); and bridled goby, *Arenigobius bifrenatus* (Kner) (4%).

I attempted to tow the test rig with the batwing and flat-rectangular pairs at similar SOGs (ranging between 1.17−1.53 m s^{-1}) but, while comparable, the mean ± SE deployment distances (833 ± 4.17 and 821 ± 4.17 m) were significantly different (LMM, $p < 0.05$; Table 5. 1). Consequently all numbers and weights are discussed per standardised distance trawled (to 500 m for convenience). Based on the deployment distances, the mean total substrate contacts of the batwing and flat-rectangular pairs were 166.68 ± 0.98 and 1312.86 ± 5.26 m^2, respectively.

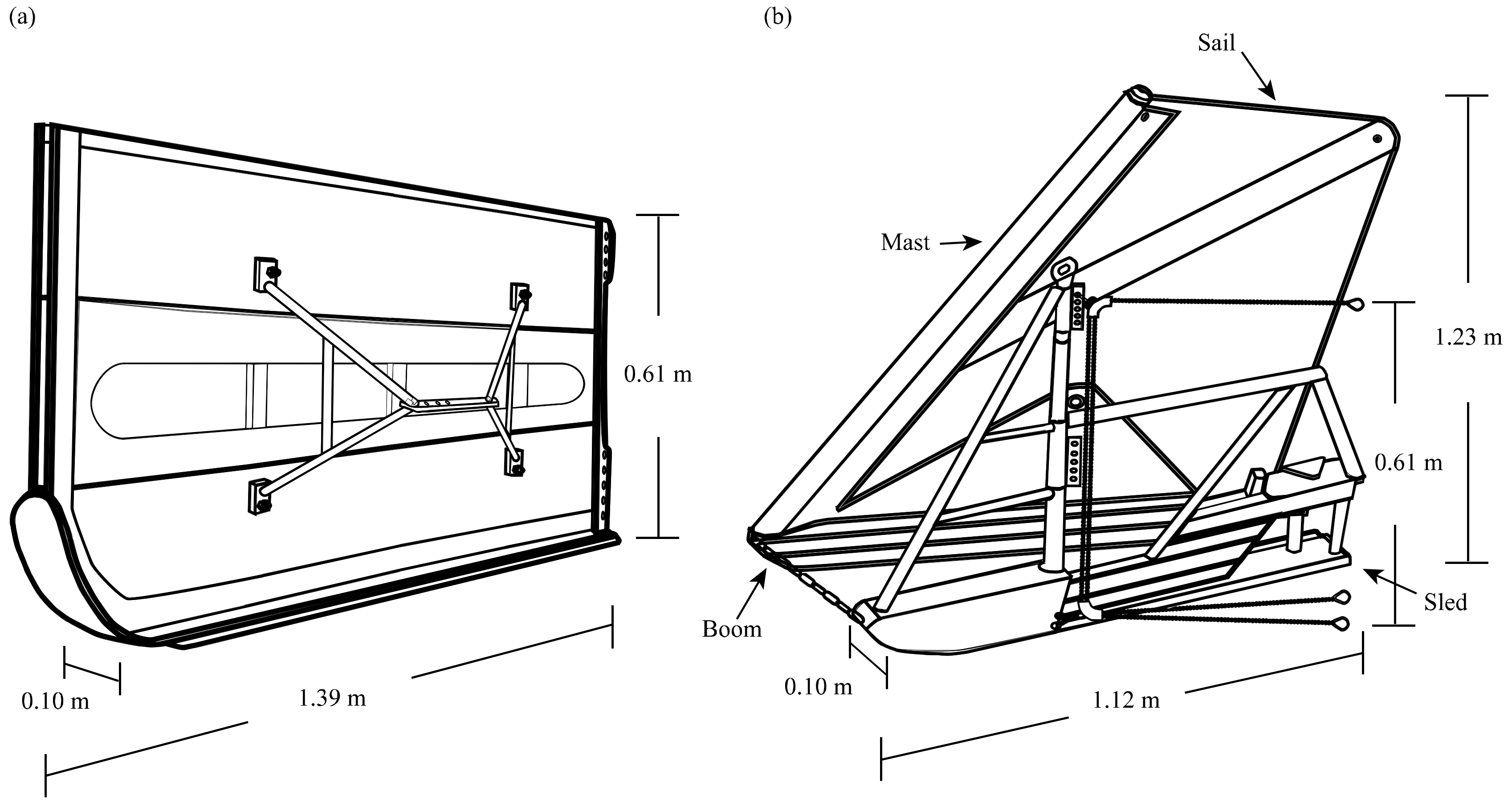

Figure 5. 1. Three-dimensional representation of the (a) flat-rectangular (1.39 × 0.61 m; 52.53 kg) and (b) batwing otter boards (1.12 × 1.23 m; 60.74 kg) tested in the chapter.

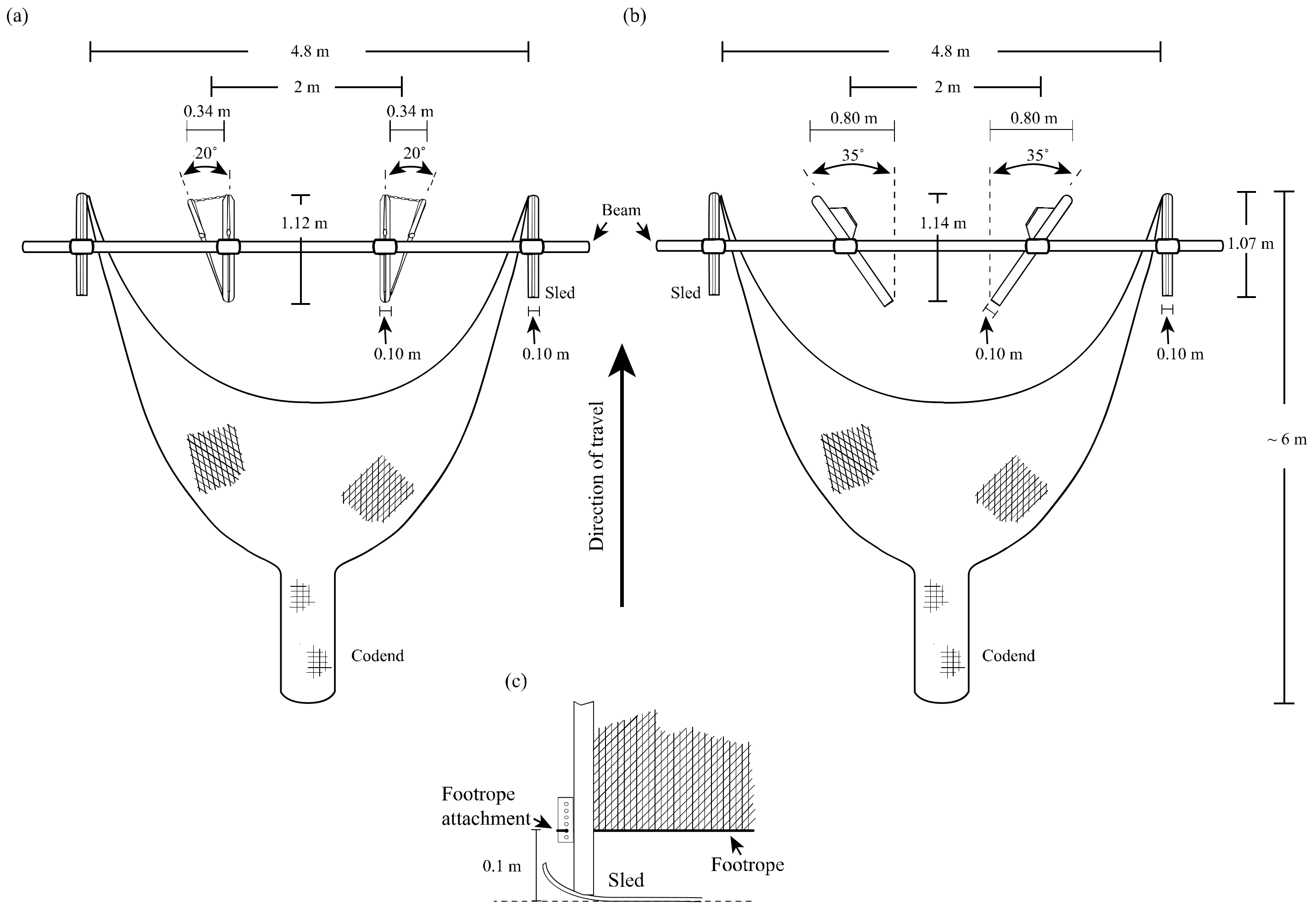

Figure 5. 2. Top view of the test-rig frame, collection net and (a) batwing and (b) flat-rectangular otter-board pairs. The highlighted section (c) shows the footrope attachment point (0.1 m from the substrate) on the leading edge of the beam-trawl sled. The recorded lengths (of the fixed and solid structures in a and b) are proportional, but owing to variable dynamics, the net shape and length were estimated.

Table 5. 1. Summaries of Wald *F*-values from linear mixed models assessing the importance of the fixed effect of otter-board pair (batwing vs flat rectangular) in explaining variability among catches in the collection net. Numbers and weights are presented in their raw form and prior to analyses were standardised to 500-m^{-1} trawled, and then log-transformed. CL, carapace length. –, not relevant.

Variables	Wt (kg)	No.	Wald *F*
Deployment distance	–	–	4.76*
Wt of total catch 500 m^{-1}	53.51	–	26.83***
Wt of school prawns, *Metapenaeus macleayi* 500 m^{-1}	2.42	–	21.56**
No. of *M. macleayi* 500 m^{-1}	–	4,794	13.32*
Wt of misc. Dendrobranchiata 500 m^{-1}	3.79	–	2.94
No. of misc. Dendrobranchiata 500 m^{-1}	–	13,219	0.57
Mean CL of *M. macleayi* > 5-mm	–	–	2.58
Wt of empty shell 500 m^{-1}	30.93	–	27.61***
Proportion of empty shell damaged	–	–	11.5*
Wt of debris 500 m^{-1}	7.74	–	6.30*
Wt of total teleost bycatch 500 m^{-1}	2.95	–	0.47
No. of whitebait, *Hyperlophus vittatus* 500 m^{-1}	–	185	6.94*
No. of bridled goby, *Arenigobius bifrenatus* 500 m^{-1}	–	55	5.89*
No. of southern herring, *Herklotsichthys castelnaui* 500 m^{-1}	–	473	0.61
No. of pink-breasted siphonfish, *Siphamia roseigaster* 500 m^{-1}	–	211	0.05
No. of Australian anchovy, *Engraulis australis* 500 m^{-1}	–	140	0.05

*$p < 0.05$
**$p < 0.01$
***$p < 0.001$

Compared to the flat-rectangular otter board's 500-m deployment^{-1}, the net behind the batwing pair had significantly lower: weights of total catch (predicted mean reduced by 80%), empty shells (by 89%) and debris (by 50%); numbers and weights of *M. macleayi* (by 78 and 72%); and numbers of *A. bifrenatus* (by 25%) (LMM, $p < 0.05$; Figure 5. 3a−e; Table 5. 1). The batwing pair also damaged relatively fewer empty shells (28 ± 3 vs 40 ± 3% of the total), but directed more (91%) *H. vittatus* 500 m deployment^{-1} into the collection net, than the flat-rectangular configuration (LMM, $p < 0.05$; Figure 5. 3f; Table 5. 1).

There was no significant difference in *M. macleayi* mean sizes (>5-mm CL) collected behind the batwing (10.31 ± 0.26 mm CL) or flat-rectangular (9.76 ± 0.26 mm CL) otter-board pairs (LMM, $p > 0.05$; Table 5. 1). Although insufficient individuals were caught to enable analyses of mean TL among deployments, the pooled size frequencies of *A. bifrenatus* and *H. vittatus* were also similar between configurations (Figure 5. 4). There were no other significant differences between treatments (LMM, $p > 0.05$; Table 5. 1).

Discussion

This study represents an innovative approach to describing the reductions in bottom contact and associated habitat disturbances that can be achieved via modifications to otter-board design. The observed relative differences in live catches and non-motile entrained material can be explained by behavioural responses and density-dependant mechanisms related to the substrate contact and AOA of the otter boards.

The results suggest efficiency differences between the flat-rectangular and batwing otter boards, but it should be noted that there was an experimental-design artifact which could potentially confound the interpretation of some variables. Specifically, the otter boards were inside the collection-net wings and closer to the opening than typical trawl configurations. Further, the necessary width of the collection net (i.e. 4.8 m in total) would have meant some organisms were caught, irrespective of the otter boards. Nevertheless, the significant increase in numbers of *H. vittatus*, but fewer *A. bifrenatus* in the net behind the batwing may reflect its greater aspect ratio and lesser bottom contact. Specifically, *H. vittatus* is a schooling species that might have more easily avoided the net behind the flat otter boards owing to their large projected area (a function of the 35^{o} AOA) and the associated visual stimulus (e.g. greater sand clouds). In contrast, *A. bifrenatus* are benthic and therefore more likely to be affected by the reduced bottom contact of the batwing.

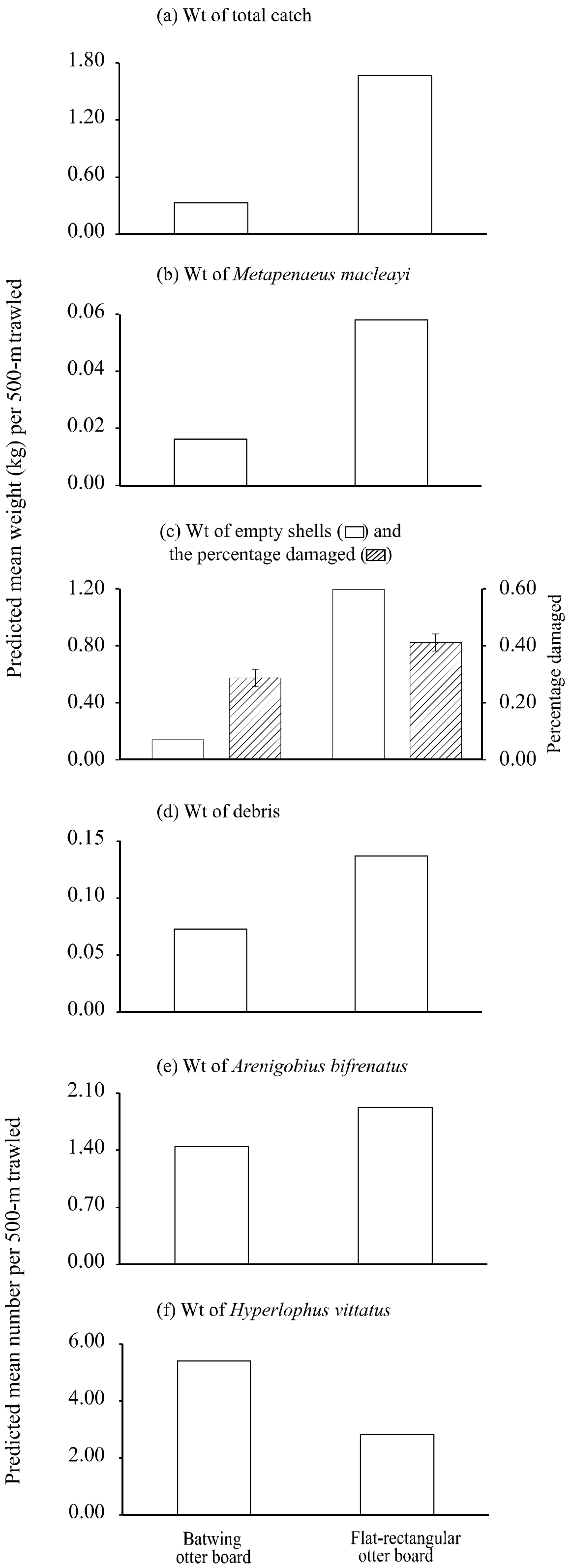

Figure 5. 3. Significant differences in predicted mean catches in the collection net 500 m^{-1} deployment between the flat-rectangular and batwing otter-boards pairs for the weights of (a) total catch, (b) school prawns, *Metapenaeus macleayi*, (c) empty shells (*Anadara trapezia* and *Spisula trigonella*, with the percentage damaged, ± SE), and (d) debris and the numbers of (e) bridled gobies, *Arenigobius bifrenatus*, and (f) whitebait, *Hyperlophus vittatus*.

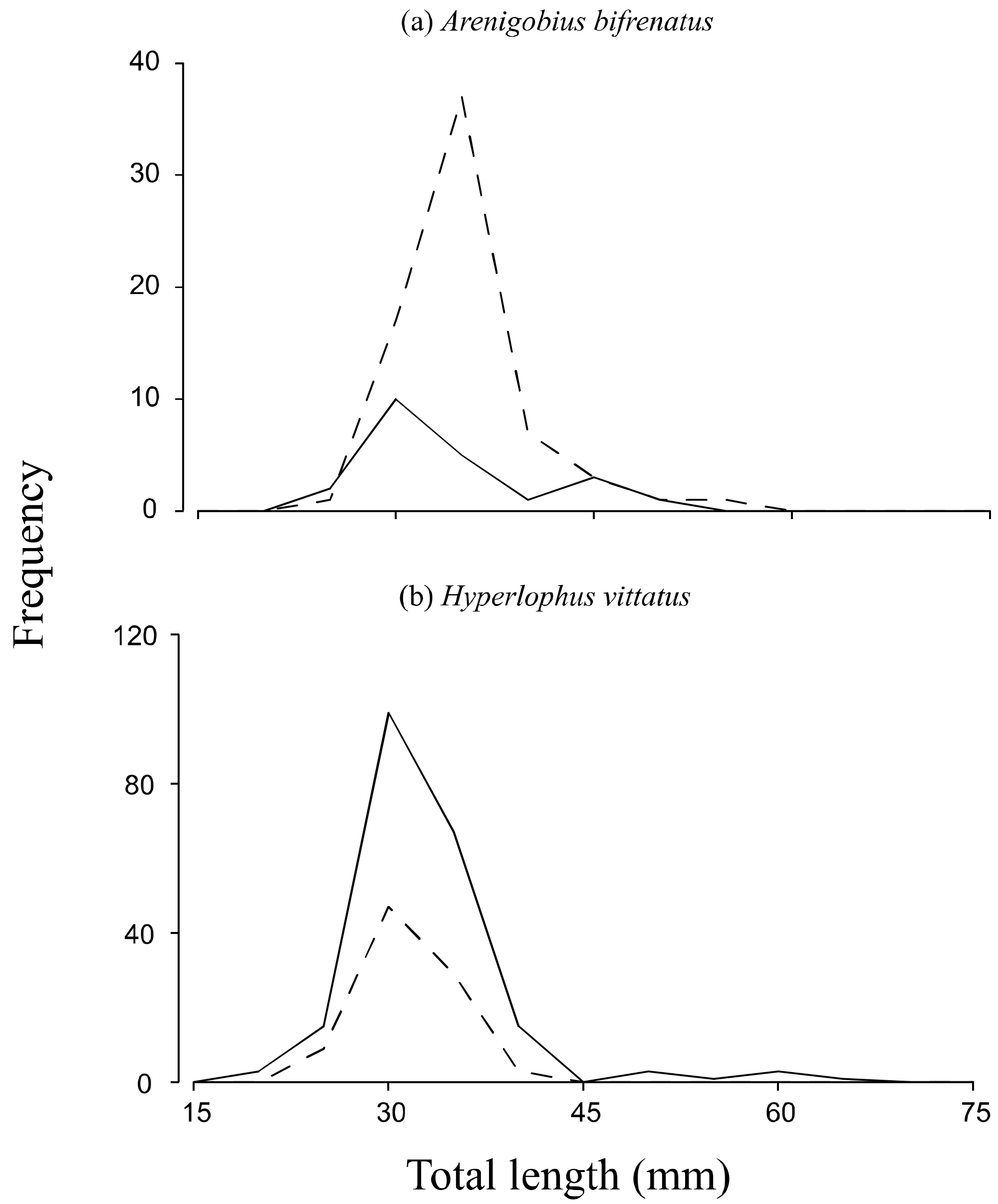

Figure 5. 4. Size-frequency plots of (a) bridled gobies, *Arenigobius bifrenatus*, and (b) whitebait, *Hyperlophus vittatus* in the collection net per absolute deployment for the flat-rectangular (dashed lines) and batwing (solid lines) otter-board pairs.

The observed differences in *M. macleayi* catches support the latter hypothesis, with relatively fewer in the net behind the batwing pair and at a rate (72−78%) almost proportional to the concomitant reduction in otter-board base-plate contact (87%). The same effects were hypothesised to account for significant differences in *M. macleayi* catches between beam (i.e. just sleds) and otter trawls previously tested in the same lake (Broadhurst *et al*., 2012), but did not extend to the batwing when conventionally rigged to otter trawls (McHugh *et al*., 2015). Such differences possibly reflect spatial or temporal variability in *M. macleayi* behaviour in terms of their level of activity and catchability (emergence from the substrate). Dendrobranchiata catches were not similarly affected here, but the glass shrimp were probably dispersed higher in the water column. Further, the small size of glass shrimp would have precluded any sustained swimming ability (e.g. Daniel and Meyhofer, 1989) or active escape response.

The relationship between entrained material and base-plate contact was further supported by the non-motile catches, and especially shells. For example, the batwing pair displaced 89% fewer shells into the collection net than the flat rectangular; almost exactly the same as the reduction in base-plate contact (87%). Further, the batwing damaged proportionally fewer shells, which may reflect the mechanism of displacement. The flat-rectangular otter board would have displaced shells along the length of the base-plate with its intense ploughing action, and guided some of the shells into the collection net by contact with the timber-and-steel hydro vane. In contrast, the batwing would have displaced fewer shells with the ramped, leading edge of the base-plate, with only some then contacting the PU sail.

While physical contact is an important factor affecting the displacement of dense material/organisms, otter boards also mobilise sediment via their hydrodynamic action (Main and Sangster, 1981; O'Neill and Summerbell, 2011). For example, the amount of material entrained by an otter board can be related to its hydrodynamic drag (O'Neill and Summerbell, 2011), because this is a measure of the rate at which energy is imparted by the otter board to the otherwise stationary water. This effect—an otter-board's AOA and resulting hydrodynamic drag—is evident from observations by Sterling and Eayrs (2008), where the water flow around a batwing's low AOA sail did not separate, and entrained less material (predominantly near its base) than a conventionally rigged flat-rectangular otter board (from which plumes filled the immediately posterior water column).

The relative difference in lighter displaced debris (mostly wood) between designs (e.g. 50%) may reflect the difference in drag of the otter boards and the energy contained in the water turbulence surrounding them while they produce a spreading force. Specifically, it is possible that while the hydrodynamic effects of both boards were not sufficient to displace shells from the sediment, it was nevertheless the key force behind the disturbance/mobilisation of less dense material (like wood) into the collection net, and the extent reflects the relative hydrodynamic drag of the boards.

The results present a useful comparison of habitat disturbance between two contrasting otter-board designs; however, it is important to consider that the consequences in terms of actual ecological impacts remain unknown. Further, the test rig precluded replicating some aspects of conventional operations, including variations in otter-board contact weight and orientation with respect to pitch (tilt) or roll (heel). Notwithstanding the limitations, I believe the method replicated commercially representative otter-board/seabed interactions and provided accurate relative indications of the characteristics of the two designs.

Considering the above, low AOA and high-aspect otter boards like the batwing clearly have the potential to displace less benthic material, and for bivalves, at least, with considerably less physical damage. Further research is required to examine the ecological implications of such reductions in various trawling environments (e.g. Kaiser *et al*., 2015), but the principles developed here might offer practical solutions where trawling in sensitive areas is considered problematic. A concomitant benefit of the batwing design is reduced drag, which has the potential to make trawling more energy efficient (e.g. McHugh *et al*., 2015).

Chapter 6: General Discussion

Thesis aims and outcomes

Improving penaeid-trawl environmental efficiency is an important consideration for preserving long-term fishery security, and the concepts presented in this thesis highlight some of the possible options available. I chose to assess spreading-mechanism modifications because this section of the trawl configuration (i) represents the initial contact for target and bycatch individuals, (ii) inflicts the greatest impacts to benthic habitats (Eigaard *et al*., 2015) and (iii) has a high drag component (e.g. >45% of the total system; Sterling, 2000 and reiterated in Chapter 3).

Using treatments from three broad categories: (i) substituting otter boards with beams; (ii) amalgamating positive environmental concepts across both methods; and then within otter trawls (iii) revising otter boards and their rigging, my main objective was to assess the most appropriate modifications to improve penaeid-trawl environmental efficiency based on reducing the three key response variables of bycatch, habitat impacts and energy intensity. While the three response variables were considered equally important here, their fundamental significance varies depending on individual perceptions. For example, reducing bycatch is considered a high priority in many fisheries from management and ecological perspectives, but fishers would be more likely to use new concepts if they perceived a realised benefit (e.g. increased fuel efficiency). These outcomes directed my principle objective to provide solutions which mitigate the environmental inefficiency associated with penaeid trawls, but had a high probability of application in a particular fishery.

Globally, beam- and otter-trawls represent the most common mobile demersal configurations used to harvest penaeids (Gillett, 2008) and, in Chapter 2, I compared these systems (with and without modifications—removing sweep wires from the otter trawls and adding a horizontal wire to the beam trawl). Comparing beam-, otter-trawls and the modifications was necessary because it helped focus the research through the remainder of the thesis by highlighting the components and/or modifications with the greatest potential for improving environmental efficiency.

The primary observations that justified further research were the utility of the counter-herding devices, termed 'simple anterior fish excluders'—SAFEs— for bycatch reduction and the potential of spreading mechanisms aligned with the tow direction to reduce drag and habitat impacts. While the results also showed that a 20% larger beam trawl had lower bycatch and drag than the otter trawl and that the sweep wires removal reduced bycatch these were not evaluated further, because they did not represent practical solutions for the studied fishery. For example, while a single beam trawl presents few issues, paired configurations are more cumbersome (than paired otter trawls), and typically not collapsible, which potentially involves additional considerations (e.g. a large deck space for storage and additional crew for handling). In my studied fishery, a small vessel (< 12 m) penaeid fishery, the operators were not particularly receptive of a paired beam-trawl system. Furthermore, the otter trawl without sweep wires also presented some potential local operational issues. First, when the net is connected directly to the otter boards it shortens the configurations' overall length which makes emptying the codend (on board) difficult. Second, removing the sweeps resulted in debris being mobilised into the wing-ends which, over time creates additional work to clear and also damages meshes.

While gear substitutions can help improve environmental efficiency, it was envisaged that fishers were unlikely to use new concepts unless they were closely related to prevailing configurations, involved limited capital investment and did not disrupt existing operational procedures. Notwithstanding the unlikely acceptance of different configurations by fishers, the beam trawl provided a reliable configuration for research purposes (e.g. Chapters 1, 2 and 5) because its rigid frame (i.e. always the same fixed opening) meant that treatments were easily standardised for SR between deployments, especially when compared to the more dynamic otter trawl.

In Chapter 3, I took one of the concepts assessed in Chapter 2—the SAFE—and tested its limitations (in terms of size) on a beam trawl before applying a reengineered version to an otter-trawl configuration. This chapter involved two experiments; the first experiment, with three different SAFEs on the beam trawl, supported the bycatch reduction results observed in Chapter 2 and highlighted the requirement to further test the SAFEs' benefits and limitations on an otter trawl. The second experiment (the SAFE on the otter trawl), resulted in some operational issues (i.e. variable wing-end spread) but the SAFE still reduced bycatch without affecting target catches, when standardised to ha^{-1} trawled.

While the lower wing-end spread caused by the SAFE on the otter trawl confounded target absolute species catches per deployment, it also presented the possibility of concomitantly improving fuel efficiency and lowering habitat impacts by reducing the otter-board AOA—if located on the leading edge. Testing the potential for the SAFE to improve fuel efficiency and lower habitat impacts was outside Chapter 3's scope, but as a concept was further progressed by Broadhurst *et al*. (2015b) and is discussed in appendix 1.

Notwithstanding the SAFE offering the potential to alter otter-board AOA, additional information was first required concerning the otter-board designs available to fishers; which may improve environmental efficiency with limited changes to existing trawl configurations. The four otter-boards compared in Chapter 4 represented a cross section of contemporary, basic and novel designs—flat-rectangular, kilfoil, cambered and the batwing. The batwing was the only otter board not currently commercially available to fishers, but was chosen for comparison because earlier research suggested it would outperform many contemporary designs (Sterling and Eayrs, 2008).

In Chapter 4, three experiments were required to fully evaluate the relative performances of the otter boards. The first experiment compared all four designs for their engineering (e.g. drag and fuel intensity) and catching performances. The otter boards with the greatest potential benefit (i.e. the lowest drag and fuel intensity) from the first experiment were the batwing and flat-rectangular designs. The remaining two experiments assessed the batwing and flat-rectangular otter boards under conventional fishing configurations (experiment 2) and with the trawls removed (experiment 3). The second and third experiments results verified the batwings' ability to outperform conventional otter boards with lower drag and fuel while maintaining trawl SR and not significantly affecting catches.

The batwing otter boards' efficiency can be attributed to their unique design—sled aligned with the tow direction and the hinged wing— which also reduces seabed contact (Sterling and Eayrs, 2008). It was this potential to lower seabed contact that formed the basis of the final Chapter (5), whereby I tested the hypothesis that the batwings would have relatively fewer bottom impacts than flat-rectangular otter boards.

To assess the potential for the batwing to reduce habitat impact, I developed a bespoke rig (from the beam and sleds used in Chapter 3), whereby attachment of pairs of full-sized otter boards (i.e. batwing and flat-rectangular) allowed relative differences on their substrate impact to be evaluated. Overall, the bespoke rig performed well and represented an innovative approach to assessing full-scale otter boards under commercially representative fishing conditions. The clear differences in impact (the batwing displaced and damaged less benthic material) presented the batwing (and via interpolation, the sleds associated with beam trawls) with another important advantage over conventional otter board designs for improving environmental efficiency. To facilitate interpretation, the significant results from my thesis are presented in a flow diagram to illustrate the relationship of each treatment to the individual response variables (Figure 6.1). It is anticipated that Figure 6.1 will be used as a quick-reference guide for individuals (i.e. fishers) interested in upgrading their trawling configuration to a more environmentally efficient system.

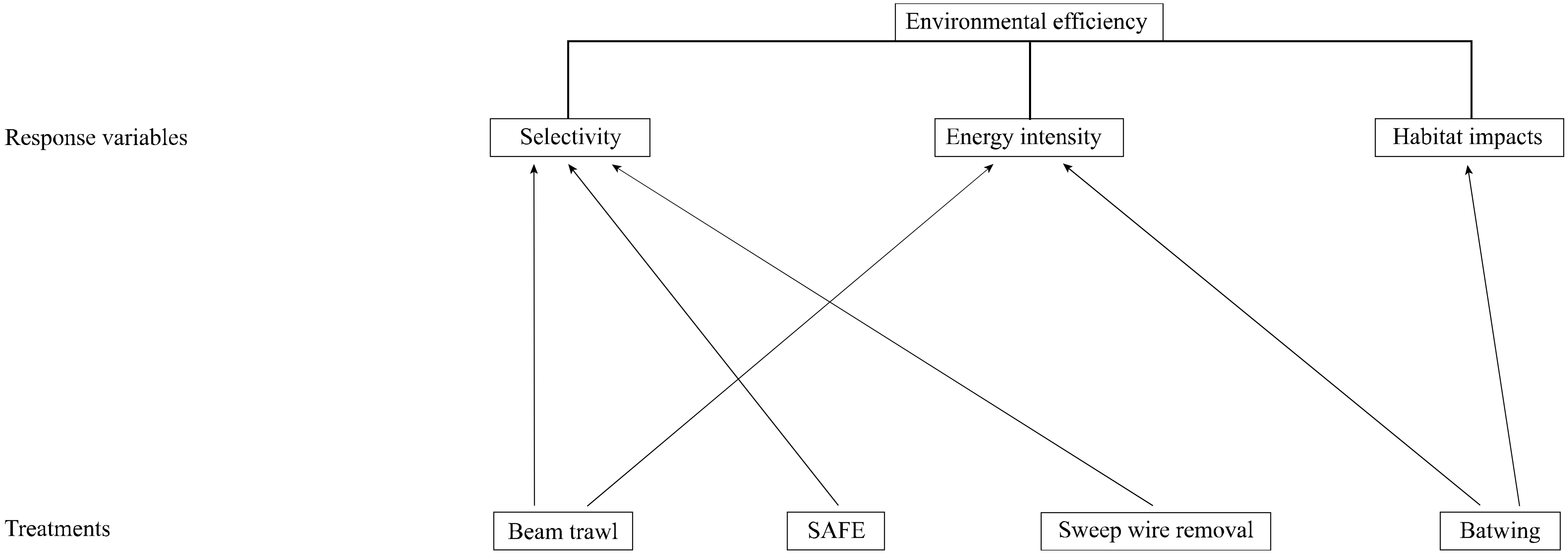

Figure 6. 1 A flow diagram showing the significant results from treatments tested in this thesis for improving environmental efficiency.

Limitations and future research

While all of the work undertaken during the experiments presented in this thesis used commercially applicable gear in a working fishery, a key limitation to the research was that all trawling was diurnal (a legislated regulation in the studied fishery). Nocturnal testing of some modifications especially important for work on reducing bycatch, because it is when many penaeid-trawl fisheries operate and the stimuli (e.g. visual and tactile) responsible for capture are likely to be different for both target and non-target species under reduced ambient light (e.g. Broadhurst *et al*., 2015d). Notwithstanding the above, in corresponding research undertaken at night, Broadhurst *et al*. (2015b) concluded that the modifications (e.g. the SAFE) had similar effects—maintaining target species while reducing bycatch. Further, there would not be any diel differences among the modifications and/or gear alternatives in terms of improving fuel efficiency and reducing habitat impacts.

Additionally, while light intensity might not affect the modifications performance it is unsure what direct effect (other than reducing light intensity) turbidity might have on the stimuli responsible for capture. Coastal regions are typically more turbid than offshore areas and many species occupying these areas (e.g. Lake Wooloweyah where the experiments in Chapters 2, 3 and 5 were undertaken) will likely be tolerant to the (potential) prevailing conditions (e.g. low visibility, anoxic conditions, etc.) (Blaber and Blaber, 1980). However, while turbidity was considered consistent within experiments (i.e. because of the experimental design's simultaneous treatment comparison), it would be advantageous in future research to collect data on turbidity along with other abiotic factors (e.g. temperature, pH and salinity) and the respective tolerance levels of the species encountered. In addition to species tolerance levels it would also be important to assess any sensory compensation (e.g. auditory or chemical cues) that could impact on visual cues during periods of higher turbidity or low-light intensity.

While the research undertaken in this thesis used one of the most common penaeid-trawl configurations—a double rig—the utility of other multi-rig systems (i.e. triple, quad and penta rigs) needs to be considered (see Appendix 1). Multi-rig systems typically are more environmentally efficient than single trawls because they have smaller and lighter components (e.g. otter boards) and nets with a lower overall twine area (e.g. Broadhurst *et al*., 2013b). The utility of the batwing otter boards and the SAFE on multi-rig systems (i.e. triple rig) were assessed by Broadhurst *et al*. (2015b), and while both had satisfactory selectivity characteristics, their engineering performance within higher-order multi rigs warrants further research.

I hypothesised that a SAFE could be rigged to reduce otter-board AOA, but I did not assess this here. However, it forms part of ongoing research within the NSW Department of Primary Industries Fisheries Conservation Technology Unit (e.g. Broadhurst *et al.*, 2015b). This research will need to focus on eliminating any potential effects (e.g. reduced SR) that may occur if the SAFE length is not correctly matched to the spread of the expected attachment points on the otter boards. Notwithstanding possible issues when attaching a SAFE to an otter trawl, it is conceivable that it could be easily applied to 'fixed width' configurations (e.g. beam trawls or dredges) where fish bycatch needs to be reduced.

Furthermore, while the batwing otter boards presented fishers with a realised benefit (lower fuel intensity) their acceptance as a replacement for conventional designs will extension activities. There are many otter-board designs available (e.g. see Seafish *et al*., 1993) that have potentially greater efficiency (e.g. lower hydrodynamic drag) than common designs (e.g. the flat rectangular). However, many fishers appear to have personal preferences for a particular otter-board design (Patterson and Watts, 1985; Sterling, 2000). In some case, such preference is likely to make it difficult for low-impact and fuel-efficient otter boards, like the batwing, to become common within fisheries without changes to their legislation where gear configurations will be required to have limited substrate contact.

The research undertaken in this thesis focused on trawl spreading mechanisms and while the results of Chapters 2–5 highlight the importance of his trawl section for improving environmental efficiency there are other components that warrant future consideration. The spreading mechanisms are heavy and constitute a large proportion of the overall trawl system drag, but it is the netting that often constitutes the largest drag component in most systems. The trawl netting will also be responsible for overall selectivity, but will not typically be important for reducing habitat impacts (e.g. Broadhurst *et al*., 2015c; d). The frame lines and ground gear will also (like the spreading mechanisms) affect all three response variables. For example, modifying the frame lines can alter the selectivity (e.g. by increasing the headline height; Johnson *et al*., 2008) and overall drag (e.g. the 'W trawl' discussed by Balash *et al*., 2015and presented in Appendix 1), while ground-gear modifications will help alleviate habitat impacts and drag (e.g. the 'soft brush' tested by Broadhurst *et al*., 2015a).

It is likely that a holistic approach is needed to improve penaeid-trawls' environmental efficiency, whereby a combination of modifications to the frame lines, ground gear and trawl body in addition to those proposed here for the spreading mechanism will be required for the greatest success; a concept that is progressed in Appendix 1. Furthermore, it is possible that apart from being legislated, modifications will only be used by fishers once they have been rigorously tested and offer greater incentives (e.g. significant cost saving alternatives) than current configurations.

The potential for other modifications to the spreading mechanisms, frame lines, ground gear and trawl body for improving penaeid-trawls' environmental efficiency warrants further discussion, but it was outside the scope of my thesis. However, as stated above, while collating the information for Chapter 1, the literature search was broadened to include the frame lines, ground gear and trawl body, with the results forming a comprehensive literature review that is now ready for peer review (Appendix 1).

While I attempted to avoid any shortcomings in the research, some were inevitable; for example, in experiments with high turbidity it was difficult to effectively use video recording equipment. However, maximising all available technology (e.g. cameras, sonar and electronic sensors), where possible, could have alleviated some limitations of the research. For example, deploying nephelometers around the trawl's catching zone to continuously record turbidity levels along with video and sonar recording equipment, could potentially have clarified some effects of different light intensities on species interacting with gear configurations/modifications.

Conclusion

The research conducted in this thesis highlights some of the possible mechanisms available for penaeid fishers to improve the environmental efficiency of their trawls through modifications to the spreading mechanisms. One of the key benefits of trawl-spreading mechanism modifications to facilitate bycatch reduction is their potential to reduce any unaccounted mortality that may occur to individuals through injury sustained from escape attempts (e.g. abrasion from the mesh and/or BRDs). The concepts proposed within my thesis also provide many other mobile demersal trawling fisheries (non-penaeid) facing the same environmental efficiency issues, with the basis of simple applied solutions for progressive assessment and refinement.

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Appendix 1. McHugh, M. J., Broadhurst, M. K., Sterling, D. J. Reducing the global environmental impacts of penaeid trawls: a review and protocol forwards. In Review *Fish and Fisheries*

Reducing the global environmental impacts of penaeid trawls: a review and protocol forwards

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Running title: Reducing impacts of penaeid trawls

Abstract

Globally, penaeid-trawl fisheries are faced with three broad sustainability issues: (i) excessive bycatch; (ii) acute benthic-habitat impacts; and (iii) high energy intensity. Most resolution efforts have focused on i above, and via bycatch reduction devices (BRDs) installed in the posterior trawl (codend) which typically reduce total bycatches by 30–70%, but are poorly adopted owing to few perceived benefits by fishers. While mandated BRDs will remain a feature of selective penaeid trawling, solutions to habitat impacts and energy intensity require changes to the anterior trawl, including the spreading mechanisms (e.g. otter boards, beams and sleds), ground gears, and net designs. Further, because such components ultimately determine which organisms enter the codend, it should be feasible to structure modifications to address all three sustainability issues, including improving selection. We sought to review the feasibility of such an approach here. Fifty-eight relevant papers were located: of which 45, 11 and 23 directly or indirectly focused on reducing bycatch, habitat impacts and energy intensity, respectively. Considering these papers, we propose a protocol for holistically improving the environmental efficiency of penaeid trawling involving: (i) selecting the most appropriate multi-trawl configuration; (ii) reducing otter-board angle of attack to ~20^{o}; (iii) minimising twine area; and (iv) optimising horizontal-trawl opening. Compared to conventional configurations, choosing alternatives within the above protocol could reduce total unwanted bycatches and habitat contact by >70%, while concomitantly lowering drag/fuel costs by >20%. The latter outcome might improve selective penaeid-trawl adoption among global fishing fleets.

Keywords

Bycatch; habitat impacts; energy efficiency; trawling; penaeids.

Introduction

Penaeid distributions and trawl configurations

Penaeid trawl designs

Three problems with penaeid trawls

A combined resolution approach

Methods

Review

Reducing bycatch

Spreading mechanisms

Frame lines and ground gear

Trawl body

Reducing habitat impacts

Spreading mechanisms

Frame lines and ground gear

Trawl body

Reducing energy intensity

Spreading mechanisms

Frame lines and ground gear

Trawl body

A protocol forwards

Select the most appropriate multi-trawl configuration

Reduce otter-board AOA to $\sim 20^{o}$

Minimise twine area

Optimise spread ratio

Conclusions

Acknowledgements

References

Introduction

Mobile demersal fishing gears are believed to have originated in 14th century England with the first records of the ‘wondyrchoun’; a modified oyster dredge for catching fish (Robinson 1996). The wondyrchoun evolved into a ‘beam trawl’—a funnel-shaped net held open by a wooden beam with skids/sleds attached at each end—that was used to target benthic fish and crustaceans (Fig. 1a). The beam trawl remained the only mobile demersal gear until the late 19th century when a new design (termed the ‘otter trawl’) was invented (Cunningham 1896; Kyle 1903a,b; Robinson 1996). Otter trawls retained the funnel-shaped net, but the rigid spreading mechanism was replaced by a pair of hydro-vanes (‘otter boards’) configured at angle of attack (AOA; typically 30–50^{o}) to hydrodynamically maintain the horizontal trawl opening (Fig. 1b).

Notwithstanding centuries of development (and ongoing beam trawl use), it was the otter trawls’ introduction and an increase in steam-powered trawlers in the late 19th century that are regarded as the beginning of the industrial fishing revolution (Garstang 1900; Gabriel *et al*. 2005; Engelhard 2009). Prior to the 1880s, the unreliability of sailing vessels for maintaining consistent speeds limited them to beam trawling across flat and relatively firm substratum and therefore targeting associated species (e.g. flatfish and rays). Steam-powered trawling allowed fishers to use otter trawls with increased vertical (headline height) and horizontal (wing-end spread) openings to explore more diverse habitats (e.g. further offshore) and target different species (Cunningham 1896; Engelhard 2009).

Demersal beam and otter trawls currently account for ~25% of the total global marine harvest (~80 million tons) and with catches from most taxonomic groups (excluding arachnoids, echinoderms, tunicates and most bivalves; Kelleher 2005; Watson *et al*. 2006). While the importance of such gears to global harvests is clear, they also are among the most controversial; typically associated with some of the largest collateral mortalities evoked through discarding a diverse assemblage of non-target individuals (collectively termed ‘bycatch’; for definitive reviews see Andrew and Pepperell 1992; Alverson *et al*. 1994; Kelleher 2005). This is especially the case for penaeid trawls which, despite accounting for only 1.5% of the total global harvest, contribute more than 27% of the annual weight of bycatch (most recently estimated at ~7.3 million tonnes by Kelleher 2005).

Penaeid distributions and trawl configurations

Penaeid trawling dates back to the start of the 20^{th} century in the USA (Captiva 1966) and currently occurs throughout tropical and temperate latitudes, with >100 species targeted across shallow (~2 m) coastal fringes and embayments to deeper (>50 m) offshore habitats. Penaeid trawlers typically range between ~8 and 25 m in length and tow various systems. In many countries, the use and/or legislation of particular trawl systems are based on either the preferential use of particular arrangements that were in place when fisheries legislation was established or, more recently, unsubstantiated perceptions about how legislated gear suited prevailing management priorities (Davies *et al*. 2009).

Notwithstanding considerable diversity, virtually all penaeid-trawl designs are deployed within one of five general anterior configurations (Fig. 2). The traditional, antiquated system involves a single trawl spread by either two otter boards or a beam (Figs 1, 2 a and b). While some small inshore vessels still tow single trawls, this method has been superseded in most industrial fisheries by multi-trawl configurations (Knake *et al*. 1958; Bullis and Floyd 1972) which offer sequential (albeit unsubstantiated in most cases) reductions in drag for the same cumulative headline length and trawl speed, facilitated by lower twine and otter-board areas (Sterling and Eayrs 2010).

Among multi-trawl systems, ‘twin’ or ‘double’ rig is the most common configuration used throughout the world and involves two trawls; each with independent otter boards or beams and bridles and towed from outriggers on either side of the vessel (Knake *et al.* 1958; Gillett 2008; Fig. 2b and h). A somewhat divergent (and less common) version of double rig is the skimmer trawl, which has a unique operating system (an L-shaped structure that is suspended from the end of each outrigger; Fig. 2i) whereby the nets remain in the fishing configuration while the codend is repeatedly brought onboard and emptied (Coale *et al*. 1994). Owing to their fishing mechanism, skimmer trawls are restricted to shallow water (<~4 m) (Hein and Meier 1995). A third version of paired trawls, is ‘dual rig’ which involves the two trawls connected at a centre sled, spread by only one pair of otter boards, and towed from the centre-line of the vessel (Ramarao *et al.* 1977; Fig. 2c).

‘Triple rig’ is used off eastern Australia and, like single-and dual-rigs, comprises only two otter boards to spread the entire configuration, but the three trawls are connected wing-to-wing at two sleds and associated bridles (Sterling 2005; Fig. 2d). In many cases, the centre trawl is slightly larger than the two outside trawls.

‘Quad rig’ is the last conventional configuration and essentially comprises a set of dual rig towed from each outrigger (like double rig) (Bullis and Floyd 1972; Fig. 2e). The most concentrated use of quad rig is in US federal waters and northern Australia. A progression from quad- to penta-rig involves simply placing a fifth net between the inside trawls, and replacing the associated otter boards with sleds (Sterling and Eayrs 2010; Fig. 2). While we are only aware of one penta-rigged vessel in Australia, the concept has some merit because it further reduces drag.

Penaeid-trawl designs

Irrespective of their spreading mechanism (beams, otter boards and sleds, or by the outriggers on the vessel) or the number of nets, like all mobile gears, penaeid trawls have evolved towards maximising targeted catches (Gillett 2008). At a basal level, such capture efficiency depends on the stimuli (tactile and/or visual) from the different components eliciting a response from the target species whereby they are encouraged into the net. While some penaeids can orientate above the seabed (during migration or reproduction), most predominantly reside within or very close to the substratum (Ruello 1973; Coles 1979; Wassenberg and Hill 1994). There are few studies describing penaeid reactions to towed gears, but similar to other crustaceans, and unlike fish, their behaviour is quite specific with responses mostly evoked by tactile stimuli (Coles 1982; Newland and Chapman 1989; Watson 1989; Eayrs 2002).

Specifically, Watson (1989) observed that penaeid (mostly the brown shrimp, *Penaeus aztecus*, Penaeidae) responses to an approaching trawl were limited to abdomen contractions after tactile stimuli from contact with the ground gear (Fig. 1a). Depending on their orientation, such contractions effectively propelled individuals varying distances away (typically into the trawl) from their initial location (depending on their size; Daniel and Meyhofer 1989). This initial escape response was repeated three to five times, after which the penaeids attempted to settle onto the sea bed and were quickly forced against mesh panels, eventually tumbling down the net and into the codend (Watson 1989).

By comparison, the reactions of teleosts (and some cephalopods) to trawls are somewhat more complex (Wardle 1986; Glass and Wardle 1989). Teleosts initially detect trawls via a combination of visual and tactile stimuli generated by moving trawl-wires and associated gear (Main and Sangster 1981), with their reactions affected by various environmental (e.g. temperature, turbidity, and salinity) and biological factors (e.g. size, perception and school density) (Wardle 1975). Most individuals orientate away from the evoked stimuli and, depending on swimming ability and physiological responses, either avoid the gear completely or are progressively herded back toward the trawl opening (Wardle 1986). Owing to compensatory movements in response to shifts in their visual field, teleosts in the trawl attempt to maintain station with what they perceive as stationary objects in a ‘current’ as they are displaced by the relative movement between water and gear (Wardle 1986; Watson 1989).

After some period, depending on species-specific swimming abilities (and especially size; Wardle 1975), teleosts invariably tire, often rise in the trawl (High and Lusz 1966) and fall back along the narrowing taper towards the codend (Wardle 1986). At this point individuals often become disorientated as crowding occurs, resulting in increased swimming speeds and random attempts at escape towards the sides of the trawl. Such movement and escape can be promoted via the forward displacement of water from the moving trawl (Broadhurst *et al.* 1996; 2000); which effectively reduces the perceived current and allows teleosts to maintain a faster swimming speed for any given energy expenditure (Videler and Wardle 1991).

The broad behavioural differences described above are reflected in the key design differences between many teleost and penaeid trawls. Specifically, schooling teleosts are targeted with relatively high-opening trawls, that have a medium-to-low (0.30–0.50) so-called ‘spread ratio’ (SR; defined as wing-end spread ÷ headline length) and often long sweeps and varying mesh sizes that are progressively smaller throughout a long body to the codend (to herd and fatigue species).

In contrast, penaeid trawls have mostly low vertical openings with a high SR (0.50–0.85) and fairly steep side tapers; primarily because the horizontal opening and bottom contact of a penaeid trawl are more important than the length. Many penaeid trawls also have so called ‘lead-a-head’ on the top panel which is designed to exploit the initial behavioural response after contact with the foot rope, and prevent individuals jumping over the headline. Because of the random movements by penaeids in the anterior trawl, mesh sizes typically are small and uniform throughout (30–50 mm stretched mesh opening–SMO; Vendeville 1990).

Three problems with penaeid trawls

The designs of penaeid trawls, including their small meshes, benthic contact and use across inshore areas synonymous with diverse assemblages of small species explains their disproportionate unwanted bycatches (Andrew and Pepperell 1992; Hall 1996; Broadhurst 2000; Broadhurst *et al.* 2006). Further, because most penaeid trawls are towed relatively slowly (e.g. <1.2 m s^{-1}), much of the bycatch comprises individuals <~20 cm TL (i.e. owing to the relationship between teleost swimming speed and size), coinciding with juveniles of often economically important species (Andrew and Pepperell 1992). This poor size and species selectivity and the high associated collateral mortalities have remained the most pressing issues facing the global management of penaeid trawling (Davies *et al*. 2009). However there exist two other broad, problematic ‘eco-efficiency’ issues.

A somewhat less vocally announced concern, and ancillary to the obvious implications that the mortality of large quantities of discarded catches has on stocks and the subsequent cascading responses throughout the food web, is the unseen mechanical impacts of penaeid trawls on the seabed

(Burridge *et al*. 2003). The key components of penaeid trawls (e.g. the ‘spreading mechanisms’ and ground gear; Fig. 1a) need to be sufficiently heavy to maintain the bottom contact required to stimulate penaeids. There is a perceived concern in some fisheries that such contact may negatively affect sessile non-target organisms (epi- and infauna) across some sensitive habitats (Hutchings 1990; Watling and Norse 1998; Linnane *et al*. 2007; Depestele *et al*. 2015).

Third, there is a more recent but growing economic impetus for lower energy consumption; attributable to the rising cost of fossil fuels and awareness about the socio-economic impacts of climate change driven by the associated CO_2 emissions (Tyedmers *et al*. 2005). Globally, some crustacean trawl fisheries use over 10,000 litres of fuel per tonne of product landed, with penaeid fisheries being among the most fuel intensive (Parker and Tyedmers 2014). The latter characteristic arises primarily because penaeid trawls require their small meshes to be made from durable twine, which translates to considerable solidity (ratio of twine area-to-area covered by mesh) and therefore drag. In many fisheries, fuel costs contribute >50% towards production costs (Funk *et al*. 1998; Thomas *et al*. 2010; Suuronen *et al*. 2012). It seem reasonable to propose that the ongoing viability of penaeid trawling into the 21st century requires a coherent, multi-faceted technological approach towards solving the above three problematic issues.

Owing to the visual impacts of large quantities of discarded bycatch, the majority of research to date has concentrated on reducing bycatch, and more specifically, mitigating unaccounted fishing mortalities through improved size and species selection of the gear and, to a lesser extent, changes to fishing operations (such as sorting in water; Broadhurst *et al*. 2006). A large percentage of the global effort in this area mostly has involved modifying the posterior sections of trawls (i.e. the codend, extension and aft belly) to include physical ‘bycatch reduction devices’ (BRDs) which were most recently reviewed by Broadhurst (2000), as well as other codend modifications like square-shaped mesh (turned 45^o and termed ‘T45’) throughout (Fig. 1c).

The earliest primary-literature studies describing penaeid-trawl BRDs date back to the 1960s (Broadhurst 2000). Many BRDs subsequently have been tested, but virtually all can be classified according to two principal design processes for separating organisms via differences in size or behaviour (Broadhurst 2000). The first category (termed 'mechanical-type' BRDs) typically comprise a grid with an appropriate bar spacing at <50^{o} AOA; often located posterior to a guiding funnel/panel to direct catches to the base and facilitate separating organisms larger than penaeids through an escape exit. The second category (termed 'behavioural-type' BRDs) often have strategically positioned openings to promote the passive escape of swimming teleosts, including those smaller than penaeids. Such designs need to either: (i) contain components (e.g. panels of mesh) that reduce relative current to a velocity (typically 0.2–0.5 ms^{-1}; Watson *et al*. 1993) where small fish are able to maintain position close to escape openings (Rogers *et al*. 1997); or (ii) be positioned where there is a substantial reduction in relative water movement (i.e. immediately anterior to the codend; Broadhurst *et al*. 2000; 2002a,b).

Many BRDs have improved the selectivity of penaeid trawls, but none are 100% effective, with total bycatch reductions nearly always <70% and mostly around 30−50% (Broadhurst 2000). Also in many fisheries, there has been resistance to adopt what are considered an additional burden to operations (i.e. no perceived benefit to fishers) (Tucker *et al.* 1997).

More recently, for some fisheries, mortalities to the remaining discards have been further mitigated via changes to on board handling practices (e.g. Broadhurst *et al.* 2008). However, a suite of environmental, technical and biological factors mean that the utility of such changes in terms of actually reducing discard mortality is restricted to inshore and estuarine, small-scale operations (Broadhurst *et al.* 2006).

Less research has been published describing solutions to address the other two broad (but inter-related) sustainability concerns associated with penaeid trawling, and especially habitat impacts; which is reflected in the paucity of literature reviews. The lack of applied research, solutions and clear directions for future work are made poignant when one considers the impacts associated with demersal trawling have been extensively studied for their short- and long-term effects on a variety of habitats (De Groot 1984; Hutchings 1990; Jones 1992). There remains a general global consensus that such recurring impacts have potentially detrimental consequences for ecosystem function and its ability to tolerate disturbance without collapsing (Thrush and Dayton 2002).

A combined resolution approach

While BRDs in codends will remain a key feature of selective penaeid trawling, it is clear that technological solutions for the other two problematic categories will require ongoing changes to the anterior sections of trawls, including the spreading mechanisms, ground gears, rigging configurations, body designs and netting materials (Sterling and Eayrs 2010; Fig. 1). Further, because these gear components determine the quantity and type of organisms that ultimately enter the codend, in many cases it should be feasible to structure modifications to address all three sustainability issues, including incrementally reducing bycatch.

There is sufficient evidence to confidently suggest the utility of simple changes to the anterior sections of trawls for reducing some impacts (e.g. Sumpton *et al*. 1989; Conolly 1992; Broadhurst *et al*. 2000), but there has not been any attempt at a coherent protocol for identifying and then progressing modifications beyond isolated experiments. Similar to the development of effective BRDs in codends, there needs to be clear delineation of what might be achievable for any particular suite of changes (through formal review), followed by adequate comprehension of the key influencing mechanisms (Broadhurst *et al*. 2007). Such an approach is a crucial step towards prioritizing ongoing strategic research and achieving industry adoption (i.e. fishers are more likely to use selective modifications if they also require less fuel).

Considering the above, our aims for this review were to first collate the primary and definitive literature describing modifications to the anterior sections of penaeid trawls to address the three stated eco-efficiency issues. Using this information, we then sought to provide a protocol for progressing future research, and a holistic approach to developing effective technological changes to penaeid trawls that reduce their overall environmental impacts and improve their economic and social outcomes.

Methods

Owing to the plethora of information available on the internet that in many cases lacked empirical data, we attempted to structure this review around only primary peer-reviewed literature that involved manipulative experiments to test the hypothesis of no effects on any of the three identified response variables discussed above associated with particular modifications. However, in some cases where there were clearly definitive, novel or noteworthy modifications in the grey literature, we have included reference. The main literature databases used were the ISI Web of Science, ProQuest and Google Scholar. Some industry and government organizations were contacted for publications not listed elsewhere.

The key search terms focussed on all anterior modifications to penaeid trawls to reduce bycatch (improve species and size selection), habitat impacts, and energy intensity (measured as either drag or fuel). Our primary focus was studies on penaeids, but where modifications to trawls to target similar shrimp species (e.g. pandalids and crangonids) had clear relevance, these were included.

Based on the results, and to facilitate discussion for resolving environmental impacts, we separated a generic penaeid trawl into three zones (Fig. 1b). The first zone (spreading mechanisms) encompassed those components between the trawler and the trawl frame lines, including the warps, bridles, otter boards, or beams, sleds, and sweeps (Fig. 1b). The second zone (frame lines and ground gear) was essentially the parabolic trawl opening and the immediate upper and lower components, including the headline (floats), fishing line and the ground-gear (chains and bobbins) (Fig. 1b). The third zone (trawl body) included all modifications from the frame lines to the end of the taper, including the mesh size, orientation, twine diameter and hanging ratio (defined as the measured lateral opening of the mesh divided by the length of a stretched mesh) and panel configurations (Fig. 1b).

We structured the review to follow a logical progression through the zones (not withstanding some overlap) with a general discussion on relevant modifications, and in some cases the theoretical concepts being postulated. Species names follow those detailed in the world register of marine species (WoRMS www.marinespecies.org; last accessed 02/10/2015).

Review

In total we identified 58 articles (of which 46 were peer-reviewed) directly related to improving the eco-efficiency of trawls targeting some 19 penaeid species, and three relevant articles on pandalids and crangonids (Tables 1 and 2). For penaeids, Australia (57%) and North America (26%) dominated the locations where studies were undertaken, with the rest completed in southeast Asia and Central or South America (Tables 1 and 2). Despite the extensive penaeid fisheries in the remaining temperate and tropical coastal countries (~20), we did not locate any relevant articles.

Modifications to reduce bycatch and habitat impacts were exclusively related to the actual trawl, but energy-intensity assessments have been split between the gear and vessel (Table 2). For the purpose of this review, reductions in energy intensity were considered where they were directly applicable to fishing practices and/or fishing gear modifications.

One reoccurring issue we identified was a lack of data describing the SR of conventional and modified trawls during manipulative experiments, which precluded calculating relative swept areas and adjusting absolute catches, habitat contact and/or drag or fuel used to meaningful standardizations (e.g. ha^{-1} trawled or 'swept area rate'; SAR). Nevertheless, wherever possible we have postulated likely differences based on related studies (where SR was quantified) and used these to discuss the relative utility of modifications.

Reducing bycatch

Poor selectivity is a common issue among all penaeid- and most benthic-trawl fisheries, and this was reflected in the quantity of located studies (45) dealing with this issue (Table 2). In general, it was clear that all three trawl zones can be modified to reduce total bycatch by up to ~85%, while maintaining target catches, which in some cases included commercially important non-penaeid catches (termed ‘by-product’) (Table 2). Bycatch reduction varied according to the zone assessed, but the spreading mechanism and trawl body showed the greatest potential. The three zones are separately discussed below.

Spreading mechanisms

Several studies assessed the utility of modifying the spreading mechanism for improving species and size selectivity, and demonstrated reductions in total bycatch of up to ~40% and individual species by ~80% (Table 2). While there could be scope for changes to the warps and bridles to reduce bycatch (given the known herding response of teleosts), we could not find any relevant studies. Rather, all work started at the otter boards or sleds (Table 2).

One of the simplest spreading-mechanism changes for exploiting behavioural responses to improve selectivity is to simply replace otter boards with a beam, primarily because the beam itself can be used to elicit visual and/or tactile stimuli that exclude teleosts (Broadhurst *et al* 2012a; McHugh *et al.* 2014; 2015a). For example, compared to otter trawls, Broadhurst *et al*. (2012a) and McHugh *et al*. (2014) observed significantly lower teleost catches ha^{-1} trawled (by up to 79%) by beam trawls in a NSW penaeid fishery targeting school prawns (*Metapeneaus macleayi*, Penaeidae). However, there were also concurrent reductions in standardized catches of school prawns (by 33%; Broadhurst *et al*. 2012a; Table 2); attributed to the absence of otter boards (and associated substrate contact). It was hypothesised that the latter implication might be overcome by simply increasing the headline length of the trawls (and beam) and still maintain good species selection (McHugh *et al.* 2014).

Irrespective of the spreading mechanism, another simple modification with the potential to alter selectivity through changes to the visual and tactile stimuli is to use higher-order multi-trawl configurations (Ramarao *et al.* 1977; Broadhurst *et al*. 2013a,b; Table 2). Multi-trawl configurations have different requirements in terms of the bridles, otter boards (or beam-and-sled configurations), sleds and sweeps than single rig; all of which have varying effects on overall selectivity (Figure 2 a, b, d–i).

In a single rig, the bridles essentially are extensions of the warps and form the same function (Fig. 1b). In beam- and multi-net configurations, the bridles form an anterior ‘V’ shape (Figs 1a and 2). It is conceivable that in configurations with smaller trawls (e.g. quad rig) the bridles’ proximity to the catching zone could alter selectivity (for shoaling species) by creating a visual (and/or tactile) stimulus that would force teleosts to the catching zone’s lateral extremities, facilitating escape. Such effects might explain the observed reduction in teleost catches for double- compared to dual-rig by Ramarao *et al.* (1977) and Broadhurst *et al* (2013a) (Table 2).

While research into exploiting the stimuli offered by the bridles and warps is lacking, the concept of altering other gear components to improve selectivity has been tested (Table 2). For example, Andrew *et al*. (1991) observed greater catches of some teleosts ha^{-1} in penaeid trawls with long single (120 m) rather than short (7 m) multi sweeps, but no impacts on invertebrates, including eastern king prawns (*Peneaus plebejus*, Penaeidae). McHugh *et al*. (2014) similarly observed that penaeid trawls with no sweeps (i.e. otter boards against the wing-end) caught 50% fewer teleosts ha^{-1} than those with 3.15-m sweeps, but also 29% fewer of the targeted school prawns. One additional issue was that the trawl without sweeps accumulated considerably more debris in the wing ends (McHugh *et al*. 2014).

Altering the herding stimulus offered by the sweeps appears to be limited to changing their length, but the concept of guiding teleosts away from the net by means of cables or wires across the front of the trawl also has been proposed (e.g. Watson *et al*. 1993; Ryer 2008; Anon 2012). As one example, Ryer (2008) postulated a ‘counter herding’ device involving diagonal wires (e.g. from one wing end across the trawl to the opposite otter board) could be used to direct teleosts away. This concept was expanded by McHugh *et al*. (2014, 2015a) and Broadhurst *et al*. (2015a) who tested a concave wire/line, with and without attachments (termed a ‘simple anterior fish excluder’—SAFE) between the spreading mechanisms (two otter boards in single-/double-rigs and an otter board and a sled in triple rig). In all trials, the SAFEs maintained targeted catches (including school prawns, eastern king prawns and legally retained invertebrates and flatfish), but significantly reduced total bycatches by up to 51%, and individual species by up to 58% ha^{-1} trawled (Table 2). Such designs are inexpensive and warrant ongoing testing for their utility.

Frame lines and ground gear

Modifications to the frame lines to improve size and species selectivity mostly have been designed to promote the escape of unwanted organisms over the headline or under the foot rope, and with reductions in total bycatch and individual species by up to ~40 and 75% (Table 2). Only a few studies have assessed the utility of reducing penaeid-trawl headline heights to improve selectivity, but in many cases this is a consequence of increasing the number of trawls within a system, because the otter boards are smaller and shorter in height (Broadhurst *et al.* 2013b).

It is clear, however, that there is delicate balance between optimising headline height for the targeted penaeids, while minimising teleost catches (Eayrs 2002; Stender and Barnes 1994; Madhu *et al.* 2015). In one of the first relevant studies, Hines *et al*. (1999) compared high (3.7 m) and low (0.9 m) headline heights in skimmer trawls (same SR) and while the latter caught less total bycatch (by ~14%), catches of brown shrimp were significantly reduced (by up to 39%). In contrast, and although SR was not standardized (and therefore the swept area) between treatments, Johnson *et al.* (2008) observed significantly fewer teleosts—southern herring (*Herklotsichthys castelnaui*, Clupeidae) and silver biddy (*Gerres subfasicatus*, Gerreidae) by ~50%—in a low- (0.8 m) than high- (1.2 m) opening otter trawl, but no significant differences in catches of school prawns. In the same fishery, Broadhurst *et al*. (2016) assessed the utility of knot orientation (and therefore panel lift and headline height), and also observed fewer of the same teleosts (by up to 67%), but also less school prawns (by 26%) in the lower-height trawl.

Other headline modifications have been assessed in non-penaeid shrimp fisheries, including so-called ‘cutaway’ designs (targeting Norway lobster, *Nephrops norvegicus,* Nephropidae; Revill *et al*. 2006) and a ‘topless trawl’ (targeting pink shrimp, *Pandalus borealis*, Pandalidae; He *et al*. 2007). Both of these trawls have their headline posterior to the ground gear to facilitate the active upwards escape of teleosts. However, the utility of these modifications in penaeid trawls might be limited, considering the known behavioural responses of most species and the need for lead-a-head to prevent vertical escape.

One series of modifications that have maintained frame-line geometries to exploit species-specific behavioural differences have involved physical barriers, either between the frame lines (Seidel and Watson 1978), or as part of more complex BRDs beneath the foot rope (Kajikawa *et al.* 1999, 2009, 2013). For example, Seidel and Watson (1978) proposed a design that involved a mesh barrier between the frame lines, and an open bottom panel with electrodes to stimulate penaeids upwards into the posterior trawl. However, owing to logistics, the concept did not gain popularity. Barriers need to cover large surface areas, be flexible and foldable, and consequently are easily clogged with debris.

In a variation of the above concept, Kajikawa *et al.* (1999, 2009, 2013) tested a generic modification to penaeid-beam trawls termed the ‘system of unwanted ramp-way filtered BRD’ (SURF-BRD). The SURF-BRD comprises a large-mesh panel at the footrope designed to direct unwanted teleosts to lateral escape exits. The device has been demonstrated to exclude some benthic teleosts—lizardfish (*Saudrida* spp. Synodontidae) and cinnamon flounder (*Psuedorhombus cinnamoneus*, Paralichthyidae)—with no effect on the targeted whiskered velvet shrimp (*Metapenaeopsis barbata*, Penaeidae) (Tables 1 and 2).

Another system that has successfully used barriers is the ‘roller-frame trawl’, which comprises vertical (between the frame lines) excluder bars evenly spaced across the trawl mouth (Tabb and Kenny 1967). However, the effectiveness of the roller-frame trawl is limited to excluding large individuals (e.g. turtles) and additional secondary BRDs are required to exclude smaller bycatch species (Crawford *et al*. 2011).

While physical barriers might not be practical in many trawl configurations, the concept of creating a deterrent (e.g. to provide either visual or tactile stimuli and similar to the SAFE) between the frame lines has been proposed. A simple method of attaching lights to the headline was suggested by Maynard and Gaston (2010), but the results were discouraging with increased total bycatch (by up to 51%). In related research, Gaston *et al*. (2012) had more positive results with an ~18% reduction in total bycatch and ~6% increase in target catches. Spread ratio was not assessed, but not expected to vary with such modifications (Table 2). Similarly, Hannah *et al*. (2015) located green light emitting diodes (LEDs) on the fishing line of a *Pandalus* trawl, and reduced the bycatch of eulachon (*Thaleichthys pacificus*, Osmeridae) by up to 91%, and with negligible impact on the target species. Considering the above, and although speculative, it is possible that the lights on the headline enticed teleosts into the trawl opening aiding capture, while lights on the foot rope attracted fish to an escape opening—between the fishing line and ground gear.

Modifying the ground gear can also alter the trawl selectivity, especially for species that react to tactile stimuli (Rose 1999; Sterling and Eayrs 2008; Broadhurst *et al*. 2015b). One modified ground gear originally described by Rose (1999) to test the injury rate of red king crab (*Paralithodes camtschaticus*, Lithodidae) passing under conventional ground gears in Alaskan benthic fish trawls and subsequently tested with penaeid trawls is the ‘soft brush’ (Sterling and Eayrs 2008, Broadhurst *et al*. 2015b) (Fig. 3b). This design comprises a buoyed foot rope from which light chain is suspended vertically (and with no horizontal ground chain). Broadhurst *et al*. (2015b) demonstrated that compared to a conventional 8-mm linked ground chain (Fig. 3a), the soft brush maintained commercial catches of school prawns ha^{-1} at existing levels but slightly increased the catches of one teleost (fork tail catfish, *Arius graeffei*, Ariidae). The latter was attributed to a greater visual stimulus precluding escape under the fishing line. Similar differences were observed between light (6-mm) and heavier (10-mm) conventional chain (Broadhurst *et al*. 2015b).

Trawl body

We located 26 papers describing experiments devoted to testing hypotheses concerning the utility of modifications to the trawl body to address size and species selectivity, and with total reductions of up to 84% (Table 2). At a broad level, much of this work has concentrated on either (i) retroactively installing mechanical-type BRDs, or shortening the conventional trawl body to (ii) facilitate teleost escape, while concurrently (iii) maintaining appropriate lateral-mesh openings to increase the contact probability for penaeids (Table 2).

Among the earliest attempts at modifying penaeid-trawl bodies to improve selection were retroactively fitted BRDs. Following attempts in *Pandalus* fisheries (High *et al.* 1969), Seidel (1975) and Watson and McVea (1977) designed separator trawls (e.g. the 'V-panel') that funnelled teleosts to an escape exit ahead of the trawl extension (Fig. 4a, Table 2). While the designs excluded teleosts (e.g. ~80% of the total bycatch—although not standardized for SR; Watson and McVea 1977) they also lost considerable amounts of targeted brown shrimp—possibly owing to clogging.

Other similar mechanical-type separating BRDs tested in the trawl body included the Morrison soft TED (Kendall 1990; Andrew *et al.* 1993; Robins-Troeger 1994) and variations (e.g. Mohr and Rauck 1979; Broadhurst and Kennelly 1996; Sabu *et al.* 2013) (Fig. 4b). The Morrison soft TED was reasonably effective; mostly maintaining absolute catches of penaeids (but see Robins-Troeger 1994) while excluding total bycatch by 24–32% (Table 2). Similar BRDs are still in use (Broadhurst and Kennelly 1996; Sabu *et al.* 2013), although the Morrison soft TED has mostly been superseded by posterior, rigid BRDs (Broadhurst 2000). One problem with anterior mesh separator panels is that beyond their propensity to clog, they are complex and not easy to install (Pearce *et al.* 1989; Catchpole and Revill 2008).

Other consistent attempts at anterior modifications to improve size and species selection have simply involved shortening the trawl by steepening the side taper (Conolly 1992; Sarmiento-Nafate *et al*. 2007; Broadhurst *et al.* 2012b, 2014a, 2015c, d). For example, although catches were not standardized to account for inter-trawl differences in SR, Conolly (1992) observed that simply shortening side taper from 1N2B to all bars reduced total bycatch by 17% while marginally increasing retained catches of sea bob shrimp (*Xiphopenaeus kroyeri*, Penaeidae). Similar results were observed by Sarmiento-Nafate *et al.* (2007), although likewise SR was not standardized. However, assuming that the same otter boards were used with the modified trawls in both studies, SR should have increased slightly owing to the reduced twine area and trawl drag.

More recently, Broadhurst *et al*. (2012b) tested the above concept and investigated the utility of reducing twine area by steepening the side taper of existing conventional two- and four-seam trawls (42 mm SMO) from 1N2B (or 25^{o}) to 1N5B (35^{o}), which effectively shortened the bodies by 35%. The consequences of this simple change were consistent within seam number (two vs four), manifesting as significant reductions ha^{-1} in catches of southern herring (by 66%) among the shorter trawls (Table 2). However, the short trawls also retained significantly fewer (by 50%) school prawns. The catch reductions were attributed to the shorter trawls increasing the probabilities of mesh encounters (for both species) and allowing southern herring to swim forwards and escape, while open meshes along the sides of the trawl bodies allowed smaller school prawns to pass through.

The above study reiterated the importance of selecting the most appropriate mesh size for the targeted sizes of penaeids (Sumpton *et al*. 1989; Broadhurst *et al*. 2000). In subsequent work in the same fishery, Broadhurst *et al*. (2014a; 2015d) reduced the SMO (to 32 and 35 mm, respectively) and tested the same hypothesis above concerning side taper, and also three other modifications: (i) reducing the stretched height of the side panel; (ii) increasing hanging ratio at the frame lines; and (iii) substituting the diamond-mesh side panels with T45 (square-shaped) mesh. Side taper and side-panel depth had interactive and varied effects on size and species selection, but compared to a conventional 42-mm trawl, all short, smaller-meshed trawls reduced the total bycatch by 57% (attributed to more teleosts swimming forward and escaping) and maintained commercial catches of school prawns. There were also incremental improvements in size selectivity for school prawns associated with both changing hanging ratio and side-panel mesh orientation. But the square-mesh side panels were by far the most effective, reducing the catches of sub-commercial school prawns by up to 72% (Table 2).

The observed variability in the extent of bycatch reduction by the short trawls described above precipitated an additional experiment to more closely investigate causal effects and more specifically, the importance of available ambient light (Broadhurst *et al*. 2015d). During this experiment, two identical trawls (both made from 35 mm SMO) that differed only in their side tapers (1N3B vs 1N5B) were compared during the night and in the day with variable cloud cover (categorized as <50 and >50%). Catches were dominated by school prawns and seven teleosts. Only two fish species—southern herring and Australian anchovy (*Engraulis australis*, Engraulidae)—along with school prawns were significantly affected by side taper, with all retained in lower numbers by the shorter trawl. For school prawns and Australian anchovy, their catch reductions mostly remained consistent irrespective of diel phase and diurnal cloud cover, but southern herring (mostly smaller individuals) only escaped from the short trawl during diurnal deployments and with <50% cloud cover; possibly through anterior meshes in response to more available ambient light.

Similar species-specific differences in response to visual stimuli may explain some of the results observed by Sumpton *et al*. (1989) who compared a monofilament polyamide (PA 0.8-mm Ø twine) otter trawl against one made from multifilament polyethylene (PE 1.1-mm Ø twine) and noted lower catches of blue swimmer crabs (*Portunus pelagicus*, Portunidae) in the latter gear (although SR was not standardized). The authors hypothesised that the result was attributed to the ability of blue swimmer crabs to detect the multifilament meshes more easily and escape. By comparison, Sterling (2012) compared four trawls with reduced twine Ø (1.1–1.4-mm) against a standard PE trawl (1.68-mm Ø) and observed an increase in catches of both penaeids and total bycatch (Table 2).

Other modifications for potentially improving selection involve alternative trawl designs that inherently encompass some of the key components discussed above (more available open meshes). One such design which has its origins in *Nephrops* fisheries, is the double bosom (or twin crown) trawl, whereby a 'tongue' section in the centre of an extended bosom section divides the wide bosom into two smaller sections giving increased ground coverage (Thomsen *et al*. 2004). While double bosom trawls are not widely used to target penaeids (Stender and Barnes 1994), a similar concept—the 'W' trawl—was developed by Balash *et al*. (2015a). The W trawl extends the double bosom concept to the headline, and while its primary objective is to lower drag, there have been encouraging results for reducing bycatch (by up to 11%; Balash *et al*. 2015a).

Reducing habitat impacts

Virtually all benthic-trawl components that contact the seabed, including those comprising penaeid trawls, potentially leave marks; the effects of which have been extensively commented on and assessed over the past few decades (Jones 1992). Comparatively fewer studies have tested applied solutions (beyond temporal and spatial closures) to reduce the benthic contact of any trawls, and even fewer have assessed the consequences of subsequent reductions. Notwithstanding the lack of quantitative data, from the available literature it is clear that the total bottom contact of penaeid-trawl spreading mechanisms and ground gears can be reduced by ~90 and 70%, respectively and with minimal impacts on the targeted catches (Table 2).

Spreading mechanisms

The direct effects of warps and bridles on habitats appear negligible, but through their variation these components indirectly affect trawl bottom contact. For example, reducing the ratio of warp-length-to-fishing depth will reduce contact pressure (Fujimori *et al*. 2005; Valdemarsen *et al*. 2007; Ivanović *et al*. 2011) while varying bridle length within a coherent range will affect SR, otter-board AOA and ultimately lateral contact (Broadhurst *et al*. 2012a). The importance of SR on ground-gear contact was illustrated by Broadhurst *et al*. (2014b), who observed a negative relationship between catches of benthic species and SR (0.5, 0.6. 0.7 and 0.8) in a penaeid-beam trawl, and presumably owing (at least in part) to concomitant reductions in the pressure of the ground gear attached to the fishing line.

Of the various trawl components, the spreading mechanisms (and associated attachments) contribute the most towards the habitat impacts associated with many mobile demersal gears (Gilkinson *et al.* 1998; Ivanović *et al*. 2011; Eigaard *et al*. 2015) including penaeid trawls (McHugh *et al.* 2015b). Such impacts are reflected in the abundance of peer-reviewed studies assessing the associated impacts of otter boards on benthic substrates and communities (e.g. Hutchings 1990; Watling and Norse 1998).

An otter board's substrate contact (and therefore potential impact) is determined by its operating AOA and length. For example, a 1-m long rectangular otter board (e.g. Fig. 5a) at 90^{o} AOA will have 1 m of lateral contact, but if same otter board's AOA is reduced to 30^{o} the lateral contact will be reduced by 50% (to 0.5 m). While otter-board lengths vary (but are usually less than 4 m), their operating AOAs typically are between 30 and 40^{o} (but can be as high as 50^{o} Patterson and Watts 1985; Seafish *et al*. 1993; Sterling and Eayrs 2010). Many traditional otter boards can function at low AOAs (<30^{o}), but it is not usually advisable because of operational issues under some conditions (e.g. instability during turning and cross currents; Patterson and Watts 1985; 1986; Seafish *et al.* 1993; or during deployments for penaeid-trawling systems; Sterling and Eayrs 2010).

Otter-board research typically has focused on improving hydrodynamics to reduce drag with only concept designs proposed for ameliorating habitat impacts (e.g. Kennelly and Broadhurst 2002). Notwithstanding the dearth of applied solutions, a concomitant result of improving hydrodynamics is less substrate contact if AOA is reduced (van Marlen *et al*. 2010; Sterling and Eayrs 2010; van Marlen 2012; McHugh *et al*. 2015c).

One novel otter-board design that satisfies the above criteria is the 'batwing', which comprises a polyurethane (PU) sail set on a stainless-steel boom and mast that acts like an independent kite with a single longitudinal connection to the trawl system via a heavy main sled made from mild and stainless steel (Fig. 5b). The batwing is configured so that the sled base-plate aligns to the tow direction, whereas the sail has a consistent AOA (20^{o}) and rides on a PU 'flap' that passes lightly over the seabed on a layer of high-pressure water for most of its length (Sterling and Eayrs 2010; McHugh *et al.* 2015c). Recent studies showed that compared to conventional configurations, the batwing maintained catches of targeted penaeids (McHugh *et al.* 2015c; Broadhurst *et al*. 2015a) but owing to nearly 90% less bottom contact, displaced some 50–89% fewer debris and bivalves (McHugh *et al*. 2015b). Further, of the bivalves that were mobilised, the batwing damaged proportionally fewer (by 12%; McHugh *et al*. 2015b).

Another method of minimising spreading mechanism base-plate contact is to simply replace an otter trawl with either a skimmer in shallow water (Coale *et al.* 1994) or, irrespective of depth, beam trawls (Broadhurst *et al.* 2012a; McHugh *et al.* 2014). Broadhurst *et al*. (2012a) and McHugh *et al*. (2014) compared otter and beam trawls in the same estuary and observed that the latter had 86 and 18% less spreading mechanism and total contact, respectively and for the same SR. However, there were concomitant reductions in the catches of school prawns ha^{-1} trawled—hypothesised to have occurred as a direct consequence of the reduced lateral spreading-mechanism contact. Such reductions may be species-specific considering they were not repeated for eastern king prawns during comparative trials of the batwing and flat-rectangular otter boards (Broadhurst *et al.* 2015a).

While the reductions in substrate contact observed by Broadhurst *et al*. (2012a) and McHugh *et al*. (2014) potentially are encouraging for mitigating habitat impacts, the implications were not assessed. Another beam trawl (the rollerframe) used to target penaeids across sea-grass beds was reported to have no significant short-term habitat effects, although there is little known about the long-term effects of repeated trawling (Meyer *et al*. 1999).

Other studies in non-penaeid fisheries have attempted to reduce the substrate contact of conventional beam trawls by adding wheels to sleds, or by incorporating hydrovanes on the beam (van Marlen 2012). One such design is the ‘sumwing’ beam trawl, which reduces substrate contact to light pressure mainly on a single shoe anterior to a hydrodynamically shaped beam. The anterior shoe controls AOA and downward pressure from the sumwing to maintain light bottom contact.

Within otter-trawl configurations and across any given headline length, it is possible to reduce spreading-mechanism bottom contact simply by choosing triple rig. For example, in an experiment comparing optimised single-, double-, triple- and quad-rigs in a single fishery, Broadhurst *et al*. (2013b) showed that even with the greatest SR, triple rig had lower otter-board and therefore total system contacts (by 29–55% and 2–6%, respectively) than double- and quad-rigs. Similar benefits can be realized by substituting double- with dual-rig (Broadhurst *et al*. 2013a) or using a penta rig, which maintains the triple-rig theme to a higher order.

Within any spreading mechanism the sweeps potentially can also impact the substrate (i.e. the sweep connected to the ground gear, which typically operate at an oblique angle of 15–25^o), with the amount depending on their length and attachment height (usually several cm above the seabed). While penaeid trawls typically do not require long sweeps (unlike fish trawls where they can be >100 m; Engås and Godø 1989) these are necessary in some configurations to limit debris from the otter boards accumulating in the nets. Also, sweeps facilitate handling of the gear at the vessel depending on the length of outriggers and the requirement for some trawls to extend around the transom of the vessel (McHugh *et al*. 2014).

Frame lines and ground gear

No studies were located attributing benthic impacts to the frame lines of a penaeid trawl, although the ground gear (including tickler chains) has received attention (Table 2). It is clear that modified ground gear that aims to reduce physical impacts must continue to physically stimulate penaeids. Similar to other fisheries and mobile gears (reviewed by He and Winger 2010), penaeid-trawl ground-gear modifications have focused on reducing continuous parabolic contact via a lateral distribution of droppers (Sterling 2005; Sterling and Eayrs 2008; Broadhurst *et al*. 2015b). In one such example, Broadhurst *et al*. (2015b) recorded 63% less lateral ground contact from the soft-brush ground gear than traditional continuous chain, and with no effect on targeted catches.

It might also be beneficial to reduce the weight of the ground gear and/or partition this weight into a lighter ground chain and an even lighter anterior ‘tickler chain’ (Broadhurst *et al.* 2015b). Tickler chains are a popular ground-gear component in some penaeid-trawl fisheries and typically comprise a light chain in front of the trawl (which in some fisheries has been electrified) to exploit the behavioural characteristic of particular species (Watson 1976). Electrifying the tickler chain would enable the weight and volume of ground-gear components to be reduced, and therefore potentially the overall habitat impact—assuming no deleterious electrical impacts (Murray *et al.* 2016).

Electrified ground gear formed the basis of electric-pulse trawls; many of which were subsequently prohibited because they were too efficient (Yu *et al.* 2007). However, a recent adaptation of the sumwing (above) and conventional beam trawls—the pulse trawl—has gained some momentum. The design essentially streams electrodes, instead of tickler chains, to stimulate target species (Verschueren and Polet 2009; van Marlen *et al.* 2014). Verschueren and Polet (2009) suggested that compared to conventional trawls targeting brown shrimp (*Crangon crangon*, Crangonidae), a pulse-trawl type configuration could reduce substrate contact by 75%.

Another novel ground gear within the non-mechanical category is the ‘hydrorig’, whereby concave (to the direction of travel) hemispheres on the foot rope direct/deflect water down towards the substrate which disturbs the sediment (and organisms) (Shephard *et al.* 2009; Fig. 3c). Similar concepts have been employed in small-scale gears for sampling tools (e.g. water-jet beam trawls; Kangas and Jackson 1998) and although currently not used commercially might reduce dependence on mechanical stimuli that also leave discernible marks on the substrate (Table 2).

Trawl body

While the netting constitutes the largest single piece (in terms of area) of the trawl configuration, under normal fishing conditions (i.e. excluding fouling) it is associated with minimal habitat impacts (Krost *et al*. 1990). We found few references to habitat impacts as a consequence of the trawl body, although the design will affect the vertical location of components and therefore the propensity for bottom contact. One simple factor is the knot orientation in the upper and lower panels. Broadhurst *et al*. (2016) observed that trawls with both panels orientated so that the knots provided negative lift contained 4× more debris (as a consequence of bottom contact) than those with positive lift. Many fishers are aware of this issue and orientate bottom panels in their trawls to provide uplift.

Reducing energy intensity

High energy intensity, and in particular high fuel-to-target catch ratios, is a global problem that affects almost all penaeid fisheries. Such concerns were reflected in the review with 40% (24) of the papers directed towards attempts at reducing drag, and therefore fuel costs while maintaining target catches (Table 2). Most of these papers were field-based, although it is clear that flume-tank work has particular utility for refining concepts, with four relevant studies located (Table 2). From the reviewed literature, it is clear that much of the focus has been on absolute drag reduction as a proxy for fuel consumption rates by refining spreading mechanisms, followed by trawl-body treatments (Table 2). Because of the relatively low contribution of ground gear to total system drag, their modification only achieves marginal benefits (Table 2).

As stated earlier, a key issue we faced when trying to review the benefits of modifications for reducing drag and fuel was standardization of either response variable among a consistent suite of covariates, including SR, towing speed, current or the distance trawled. Some of these variables can be encompassed within the term SAR; analogous to ha^{-1}. However, like for catches, reference to standardized SR (which was attempted within several studies assessing modifications to reduce system drag components) also directly implies attempts at standardization among comparisons.

Spreading mechanisms

The importance of the spreading mechanisms with respect to overall drag was evidenced by 15 reviewed manuscripts focusing on this anterior zone (Table 2). The overall drag associated with modifying this zone was up to ~20% lower than conventional gears (Table 1). There were very few attempts at assessing standardizations among gears (e.g. drag for a given SAR), and so most estimates are absolute.

We could not find any references assessing the utility of reducing warp diameter nor other towing cables for penaeid trawls as a means for mitigating drag. It is possible that the drag of trawling warps can be considered negligible because penaeid trawling is typically undertaken in shallow (<50 m) areas.

Like for reducing bycatch and benthic impacts, a simple method of reducing drag among single- or double-rigged otter trawls is to replace the otter boards with a beam. When comparing otter- and beam-trawling in the NSW penaeid fishery, Broadhurst *et al*. (2012a) observed that the latter had significantly lower drag (by 10%). In the same fishery, McHugh *et al*. (2014) used a more hydrodynamically shaped beam which contributed toward s a total system drag reduction of up to 31% less than the otter trawls.

In other non-penaeid fisheries, rollers have been added to the beam ends on conventional designs; potentially reducing drag especially on firmer substrates. Even greater benefits can be achieved via the use of more hydrodynamic designs such as the sumwing (van Marlen 2012). Preliminary trials of the sumwing imply considerably lower drag than conventional systems. The challenge would be to apply the concept to penaeid trawling, whereby the close proximity of the beam to the seabed does not negatively affect behavioural responses.

Within otter trawls, and like for improving species selectivity, the other common (and among the earliest) method for reducing otter-trawl drag is to use high-order multi-net configurations (Knake *et al*. 1958; Bullis and Floyd 1972; Ramerao *et al.* 1977; Broadhurst *et al*. 2013a; 2015a). Early predictions that substituting single- with double- (Knake *et al*. 1958) and double- with quad- (Bullis and Floyd 1972) or dual-rigged trawls would offer reductions in drag were subsequently realized and evidenced by the common use of multi-trawl systems (e.g. double rig) globally (Gillett 2008). More recently, Broadhurst *et al*. (2013b) concomitantly assessed single-, double-, triple- and quad-rig configurations (all with the same cumulative headline length) and found that compared to single rig, the multi-trawl configurations reduced drag by 7, 11 and 10%, respectively. In related work, Broadhurst *et al*. (2013a) observed that a dual rig had 24% less drag than a double-rig configuration. These observations also support broad differences proposed by Sterling and Eayrs (2010) from a simple numerical model.

Irrespective of the configuration, drag can be further mitigated via otter-board modifications (Haby and Graham 2014; McHugh *et al.* 2015c). Typically, otter boards need to be sufficiently heavy to make seabed contact and rigged to operate at an acute AOA to hydrodynamically force themselves apart, opening the trawl mouth to the desired SR. Consequently, the easiest option to reduce otter-board drag is to improve their hydrodynamics and lower AOA. While many otter boards can function at lower AOAs (e.g. 20–25^{o}; Seafish *et al*. 1993) for fish-trawling systems (low SR) there are few commercial designs available for penaeid trawling (high SR); primarily owing to operational issues associated with the lower hydrodynamic forces (Patterson and Watts 1985) and deployment stability. While much of the work on improving otter-board hydrodynamics comes from controlled experiments in flume tanks, there have been a few successful attempts at generating a reliable low AOA design for use in penaeid fisheries; specifically addressing associated rigging issues (Sterling and Eayrs 2010).

When Sterling and Eayrs (2010) first field tested the batwing, the overall drag reduction was assessed as 13% with 5.5% greater SR. Based on these results, it was expected that a later version would require 20–25% less fuel than conventional double-rigged otter boards for the same SAR performance. Subsequent comparative trials by McHugh *et al*. (2015c) support these estimates with mean drag and fuel up to 18 and 14% less than conventional flat-rectangular, kilfoil and cambered otter boards for the same SR and speed. The same drag benefits were not observed in triple rig, but this was attributed to the used of sleds which reduce the contribution of the spreading mechanism to overall system drag (Broadhurst *et al.* 2015a).

Another option is to increase the aspect ratio of otter boards to improve efficiency (by facilitating maximum lift at a lower AOA). It has been demonstrated that in non-penaeid, demersal-trawl fisheries, replacing dotter boards with semi-pelagic designs can eliminate substrate contact and reduce drag and fuel (e.g. by up to 12%; Eayrs *et al*. 2012). While the same concept might apply to penaeid trawling, there is the potential loss of tactile stimulus contributing towards capture (Broadhurst *et al* 2012a). Any such impacts might be offset by slight compensatory increases in foot-rope length, although additional design modifications would be required to account for greater twine area and drag.

Posterior to the otter boards, the sweeps (when) used with penaeid trawls typically are short and unlikely to directly affect drag. But sweeps do influence the drag of other components. For example, McHugh *et al*. (2014) noted that compared to an otter trawl with 3.15-m sweeps, the same trawl without sweeps had a significantly greater SR (0.67 vs 0.71), which concomitantly slightly increased drag (albeit non significant). The latter indirect impact highlights an important relationship between even slight variations in SR and trawl engineering performance reiterated by Broadhurst *et al*. (2014b). In the latter study, increasing SR from 0.5 to 0.6, 0.7 and 0.8 positively affected total system drag (and negatively affected catches), with the 0.5 SR requiring 16% less force to tow than at 0.8. This outcome can be explained by the concomitant increase netting angles in the trawl body as SR increases and the importance of this area on overall engineering performance.

Frame lines and ground gear

The frame lines contribute toward hydrodynamic drag, while the ground gear evokes both hydrodynamic and contact drag. We located very few studies that quantified or implied the effects of ground-gear changes on total system drag (Table 2). In most cases, ground-gear changes designed to improve selectivity probably concomitantly increased drag as a consequence of greater twine areas owing to more components (Pease and Seidel 1967; Boonstra and De Groot 1974; Seidel 1979; Table 2). We only located two studies that either directly or indirectly sought to reduce drag via modifications to the frame line or ground gear (Table 2).

The first relevant study was an indirect consequence of altering the trawl configuration, via the W trawl. Specifically, re-engineering the frame lines of this design involved transferring much of the load onto a central bridle via double bosom and crown (headline) modifications. These modifications give the frames lines a W shape and reduce overall drag by reducing load on the wings where smaller otter boards are used, while maintaining SR (Balash *et al*. 2015a).

The second relevant study involved quantifying the contribution of ground gear to total drag for a generic penaeid-trawl system and then assessing the utility of modifications. Specifically, Broadhurst *et al*. (2015b) tested the drag of four ground gears—the soft-brush, and 6-, 8- and 10-mm chain. The results showed that ground gears accounted for 15–20% of the total system drag for a beam trawl and the modifications tested could reduce drag by up to ~5% across the same SR.

Trawl body

We located nine manuscripts describing modification to trawl bodies to reduce drag, with the key techniques involving minimising twine area, either via larger and fewer meshes, or thinner twine (Table 2). The mechanisms by which these changes can be evoked are somewhat varied.

It has been estimated that depending on the penaeid-trawl configuration, the netting can account for up to ~80% of the overall drag (Sterling and Eayrs 2010). Multi-net configurations help alleviate drag by lowering the amount of netting for the same combined headline length, and therefore the required spreading force (and otter-board size). For example, five 4-m (headline length) trawls will have approximately half the netting drag of a single 20-m net (Sterling and Eayrs 2010). Consequently, choosing higher-order systems has a direct benefit in terms of reducing twine area.

While the lower drag of multi-net configurations will reduce overall fuel consumption, it should be noted that it is difficult to partition individual trawl components for assessment, especially outside of a flume tank. For example, the drag benefits reported by Broadhurst *et al*. (2013b), for multi- vs single-rig systems, were not exclusively due to the reduction in overall netting area. Rather the spreading mechanisms would have had a contributory influence. In fact by removing the netting from the system (and just having wires between the otter boards) McHugh *et al.* (2014) estimated this contribution at 56% for a single trawl.

Notwithstanding the difficulties in partitioning the drag of individual trawl components, manipulative experiments provide a reliable alternative for estimation, especially when small changes are made to the trawl. For example, Broadhurst *et al*. (2012b) maintained otter-board size, but changed the side taper from long (1N2B) to short (1N5B) and detected a 4.3% drag reduction for a marginal but significant increase in SR. In related work by Broadhurst *et al*. (2014a), short (1N5B) and long (1N3B) nets, both with deep and shallow-wing end panels had up to 18% less drag than conventional gear, which was attributed to the reductions in twine area. While simply shortening the side taper of existing trawls can reduce drag, alternate designs potentially provide better outcomes. For example, Balash *et al*.'s (2015a) W trawl provided ~20% drag savings over conventional trawls within double-rig.

In addition to minimising twine area in trawls or re-configuring their load distribution to reduce the size of the spreading mechanism, using thinner twine will also help alleviate drag (Sumpton *et al.* 1989). The advent of synthetic materials (mid-20th century)—which are much stronger than natural fibres—allowed larger trawls without excessive drag, and was a major factor in increasing fishing power (Valdemarsen 2001). With synthetic materials constantly evolving (e.g. getting thinner and stronger) and becoming more affordable, their use in many fisheries is becoming more common.

High-strength material (e.g. Dyneema®) can be manufactured with a smaller diameter than lower-strength materials like PE, which has been a common net-making material for >50 years. Sterling (2012) field-tested a standard PE trawl against four made from high-strength netting and found the latter required up to 21% less fuel across standardized SRs. While high-strength netting can alleviate drag, high costs have precluded their use in many small-scale penaeid fisheries. Another variable that can affect drag is mesh orientation, with Balash and Sterling (2012) observing 12% more drag for high-strength netting that was orientated at T90 (i.e. rotated 90^o) than when conventionally orientated (Table 2).

A protocol forwards

Considering the reviewed literature, we propose that the three eco-efficiency issues associated with penaeid trawling of poor selectivity, habitat impacts and energy intensities can be dramatically and concomitantly—at least for energy intensity and either of the other two variables—mitigated by employing one or more of four groups of modifications to the anterior trawl; the selection of which will be largely affected by the targeted species and unwanted bycatches. As a starting point, we suggest first selecting an appropriate multi-trawl configuration (and without retroactively fitted netting panels or BRDs in the anterior body). Second, if the spreading mechanism involves otter boards, their AOA should approach ~20^o. Third, the twine area needs to be minimised. Irrespective of these modifications, a fourth all-encompassing operational variable is to maintain an appropriate SR for the design configuration. The relative utility of these strategies can be discussed according to the underlying biological and engineering consequences, and used to identify practical solutions for the future refinement of anterior gear modifications.

Select the most appropriate multi-trawl configuration

A simple method for minimising all three eco-efficiency issues is to first select the most appropriate conventional configuration; a decision that will largely depend on fishery-specific operational characteristics and existing legislation. It is clear that where a single trawl is desired, then beams and possibly their derivatives (e.g. winged trawls) could be a good option. Beam trawls inherently are easy to tow, and potentially can have good species selectivity owing to a solid structure scaring fish away from the front of the trawl (via either visual or tactile stimuli). If necessary, within any fishery regulated by maximum headline length, the size of a beam trawl might be increased slightly to compensate for any loss of target catches due to the loss of bottom contact by otter boards. Beams might also be used in higher order multi-trawl configurations, but appropriate methods of storing and deploying the gear for the small trawlers used to target penaeids (e.g. perhaps some sort of joint in the middle of the beam to facilitate handling on board) are required (Gillett 2008).

There seems little point in retroactively positioning mechanical-separating BRDs (made from meshes) in anterior trawl bodies spread by either beams or otter boards; primarily because of the increase in drag as a function of their twine area and, in some cases, propensity for blockages. Rather, the utility of rigid-type devices designed for the smaller surface area of the codend (and with less drag) should be promoted (Broadhurst 2000).

Within otter-trawl systems, there seems minimal utility in promoting single gear, unless large fish are a desired by-product. Perhaps a more suitable strategy is to use quad- or double-rig in shallow water, while triple rig is a safer option in deep and/or rough water or with current; primarily because the towing blocks are closer to the vessel centre line (with associated implications for stability) and the trawls can be more easily retrieved after fouling on the seabed because (like single rig) they can be winched up with considerable force without causing any vessel angle of roll.

By definition, increasing the number of nets reduces twine area (and therefore drag and required fuel). Also, because sleds are used in quad-, triple- and penta-rigs, they require fewer otter boards and less total system contact (and presumably habitat-impact reductions). As one example, Broadhurs*t et al.* (2013b) showed that for the same vessel (10 m and 89 kw), triple- and quad-rigs had up to 55% less base-plate lateral contact than double- and single-rigs. Even with their greater SRs, triple- and quad- rigs still have less overall bottom contact (by up 9% over double rig).

Although relatively few studies have been done to assess the utility of alternative ground gear, irrespective of the spreading mechanism or trawl configuration, further reductions in bottom contact could be realised by using alternate systems like the soft brush or derivatives (Rose 1999). Compared to conventional, chain ground gears, the soft brush had 63% less bottom contact, without affecting target catches. Other ground gears warrant assessment, and possibly those including angled cups to displace water downwards to stimulate prawns via hydrodynamic pressure instead of physical contact.

Such configurations have been proposed for use with scallop dredges and would greatly minimise the bottom contact of benthic otter trawls (Shephard *et al*. 2009).

Another method of minimising ground-gear impacts might be to use electricity (Soetaert *et al.* 2015). Additional experimentation is required to establish the relative species- and size-specific reactions of penaeids and teleosts to gauge the potential for improved selectivity without negative side effects on benthic animals or excessive predation while animals remain ‘affected’ by the electrical stimulation (Murray *et al*. 2016). Any increases in catch efficiencies also require quantification so that effort corrections can be made to offset changes in fishing power, which may be possible in some fisheries with effective effort regulation (e.g. Australia), but not others (e.g. China; Yu 2007).

Any reduction in otter-board height associated with more trawls within a system (especially for quad- or penta-rig) would concomitantly reduce headline height (e.g. by >16% of a double rig); a modification shown to reduce some teleost catches in other trawls (e.g. Rose and Nunnallee 1998). Reduced headline height also reduces drag, while Broadhurst *et al.* (2013a) observed that fewer otter boards may translate to fewer small fish being herded into the trawl.

Quad rig encompasses the same three-wire bridle configuration as dual rig, and might return similar benefits in terms of bycatch reduction. One limitation of quad- or penta-rigs is the need for up to five codends, which can increase on-board handling and BRD maintenance. A possible solution to this issue while maintaining the three-wire bridle-configuration benefits is to use tongue (Watson *et al.* 1984; Table 2) or W trawls (Balash *et al.* 2015a).

Irrespective of the most appropriate multi-trawl configuration, it is also clear that additional stimuli in front of the spreading mechanisms can promote some teleost avoidance. Some BRDs have been tested, but more work is required to investigate the concepts proposed by Ryer (2008). Configurations might be rigged further forward of the trawl, including via the three-wire bridle in quad rig or a tongue/W trawl, or some similar arrangement with double- or triple-rigs (Fig. 2b and d). Ideally, to prevent fish entering the trawls, such BRDs would have convex, rather than concave shapes. The testing of these designs might be expanded to include the utility of other stimuli, including light (Gaston *et al.* 2012; Hannah *et al*. 2015). Any such BRDs would need to be designed so that they can pass through the blocks (and possibly the winch) on the vessel and do not negatively affect drag (see below).

Reduce otter-board AOA to ~20^{o}

The second key step in our proposed protocol is to strike a balance between the maximum effectiveness and efficiency of otter boards, which can be approached when the AOA is ~20^{o} (an outcome that also reduces bottom contact). For conventional designs, as suggested above, one option for optimising AOA might be to locate a SAFE-type BRD between the leading edges. Broadhurst *et al.* (2015a) demonstrated functionally in reducing the otter-board AOA in triple rig using such a device (between an otter board and sled), although the greatest benefits should be between paired otter boards in double- or quad-rigs. Restraining otter-board pairs to ~20^{o} AOA should have significant benefits for the drag of these systems and warrants further testing.

Other simple, retroactively fitted options still need to be explored to reduce conventional otter-board AOA during fishing, but in the interim novel designs like batwing (and perhaps other designs; Shen *et al.*, 2015) offer a real solution for not only minimising drag (by up to ~20%), but also bottom contact. The batwing has a comparable cost to conventional otter boards, and is a viable option in those fisheries where there are concerns over habitat impacts. For example, a batwing or similar sled-type spreading mechanism (e.g. beam) can reduce the heaviest contact of a prawn-trawl system by nearly 90%. While there are no data on the consequences of such a massive reduction in otter-board contact, intuitively the benefits might include at least some reduction in collateral mortalities of targeted penaeids and sedentary organisms. In any case, such designs shouldn't negatively affect the target catches. Other, novel otter boards warrant testing, including modifications to conventional designs to minimise their bottom contact (Kennelly and Broadhurst 2002). Further work is required to more closely assess the habitat benefits of any such modifications.

Minimise twine area

Once an appropriate trawl configuration and either spreading mechanisms or otter-board type have been selected, the third step in the protocol is to minimise twine area. Within this theme, the most important preliminary criteria are to optimise mesh size for the targeted species and minimise the twine diameter (Broadhurst *et al.* 2014a). Within a design, maintaining the frame-line tapers, but shortening the body by steepening the side taper and/or reducing wing height seems one of the simplest mechanisms for reducing the twine area and therefore drag (Table 2).

Equally importantly, shortening the trawl body consistently facilitated the escape of some teleosts; either from the mouth of the trawl, or through the opening of a codend BRD (Conolly 1992; Sarmiento-Nafate *et al.* 2007*;* Broadhurst *et al.* 2014a; 2015c, d). Owing to their limited behavioural responses to trawls, penaeids appear to be less affected by shorter nets than teleosts. Such modifications can simply be made to most existing penaeid trawls and for new nets should represent cost savings owing to the reduced twine area.

In addition to minimising the wing height to concomitantly reduce trawl body length, it seems that like for other benthic trawls (Catchpole and Revill 2008), placing strategic panels of alternate mesh orientation in key positions as part of the perimeter geometry (as opposed to BRDs)—such as along the side panels—can potentially provide benefits in terms of size selectivity. Considering Broadhurst *et al.* (2015c), the utility of larger panels of T45 or T90 meshes in the sides and/or the top body of penaeid trawls warrant investigation for their utility in improving selectivity.

Optimise spread ratio

Irrespective of the anterior configuration or the design, because SR directly or indirectly affects all three eco-efficiency issues it is imperative to achieve optimal values within penaeid trawls; making this an important last step in any attempts at improving environmental efficiencies. Very few empirical data are available describing the effects of SR on penaeid trawls (but see Broadhurst *et al.* 2014b), although it is well established that the SR in benthic-teleost trawls can vary according to a plethora of technical and environmental factors including the towing speed, current, sea conditions, bottom type, warp length and fishing depth (e.g. Engås and Godø 1986, 1989; Fujimori *et al.* 2005; Weinberg and Kotwicki 2008). Even subtle variations in the SR of teleost trawls can change the geometry (including headline height) sufficiently to ultimately affect catches (e.g. Rose and Nunnallee 1998; Weinberg and Kotwicki 2008) and drag (Sala *et al.* 2008).

The few available studies suggest the above impacts extend to penaeid trawls, with a clear reduction in catches ha^{-1} with increasing SR (Broadhurst *et al.* 2014b). Such catch implications might be explained by similar effects of shorter trawl bodies, with more penaeids escaping from the wider-spread trawls owing to their steeper netting panels and some teleosts more easily detecting the trawls and not entering. But, unlike shortening the trawl body which reduces twine area, steeper netting in an over-spread trawl simply increases resistance and therefore drag and in the case of otter trawls requires larger otter boards—hence even more drag (Broadhurst *et al*. 2014b).

Notwithstanding the above, if the mechanisms for target catch loss can be closed, increasing SR means a greater swept area which creates the potential for improved absolute catches of some species. This is relatively important because if catch per SAR can be maintained across SR, the penaeid-trawl operation would be optimal at high SR (i.e. about 0.85), particularly for high-order multi-net systems, and the drag-per-unit-of-catch would be substantially minimised (12% in a hypothetical case presented by Sterling and Eayrs 2010).

Conclusions

Penaeid-trawl fisheries face serious sustainability issues that encompass both ecosystem impacts and energy usage. This review sought to provide clear direction for ongoing strategic fishing-gear research to address these broad concerns.

The first aim was to identify/isolate physical modifications to the anterior trawl that provide a range of positive inputs towards holistically minimising the three key eco-efficiency issues of bycatch, habitat impacts and energy intensities. Unlike considerable past research to develop BRDs in codends that have implied few perceived short-term benefits to industry and consequently wide-scale international resistance towards adoption (Tucker *et al.* 1997), the energy savings associated with anterior modifications should help to encourage implementation. Ultimately, the apparent reductions in unaccounted fishing mortality associated with enhancing the anterior escape of unwanted organisms and or minimal contact (which should exceed those observed for BRDs) should contribute towards improving sustainability.

The key categories of modifications reviewed here encompass spreading mechanisms, ground gear, and the trawl body; with various individual and cumulative benefits. Combinations of appropriate modifications (e.g. low AOA otter boards, short trawls and low-impact ground gear) in some fisheries would reduce drag (and therefore fuel) by >20% and total bycatches and system bottom contact by >70%; all without significantly impacting on target catches (Table 2).

While there are fishery-specific considerations in terms of the transfer and extension of such modifications, the reviewed literature and commonality among attempted solutions mean the key concepts remain valid and should see similar benefits realised across different fisheries. Such ongoing strategic research could provide solutions to mitigate environmental concerns as they eventuate, and clearly should be a future research priority for what might be considered the most topical and at times controversial commercial fishing methods.

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Table 1 Alphabetical list of the group, family, scientific and common names of organisms mentioned in the text. Nomenclature follows WoRMS (2015).

Family name	Scientific name	Common name
Crustaceans		
Crangonidae	*Crangon crangon*	Common shrimp
Hippolytidae	*Tozeuma carolinense*	Arrow shrimp
Lithodidae	*Paralithodes camtschaticus*	Red king crab
Nephropidae	*Nephrops norvegicus*	Norway lobster
Pandalidae	*Pandalus jordani*	Ocean shrimp
	Pandalus borealis	Pink shrimp
Penaeidae	*Metapenaeopsis barbata*	Whiskered velvet shrimp
	Metapenaeus bennettae	Green tail prawn
	Metapenaeus dobsoni	Kadal shrimp
	Metapenaeus endeavouri	Blue Endeavour
	Metapenaeus ensis	Red Endeavour
	Metapenaeus insolitus	Emerald Shrimp
	Metapenaeus macleayi	School prawn
	Parapenaeopsis stylifera	Kiddi shrimp
	Penaeus aztecus	Brown shrimp
	Peneaus brevirostris	Crystal shrimp
	Penaeus duorarum	Pink shrimp
	Penaeus esculentus	Brown tiger prawn
	Penaeus latisulcatus	Brown tiger prawn
	Peneaus plebejus	Eastern king prawn
	Penaeus semisulcatus	Grooved tiger prawn
	Penaeus setiferus	White shrimp
	Peneaus stylirostris	Western Blue Shrimp
	Peneaus vannamei	Whiteleg shrimp
	Xiphopenaeus kroyeri	Seabob shrimp
Portunidae	*Portunus pelagicus*	Blue swimmer crab
Molluscs		
Arcidae	*Anadara trapezia*	Sydney cockle
Loliginidae	*Loligo* sp.	Squid
Mactridae	*Spisula trigonella*	Triangular trough-shell
Teleosts		
Ariidae	*Arius graeffei*	Forktail catfish
Clupeidae	*Herklotsichthys castelnaui*	Southern herring
Engraulidae	*Engraulis australis*	Australian anchovy
Gerreidae	*Gerres subfasciatus*	Silver biddy
Gobiidae	*Arenigobius bifrenatus*	Bridled goby
Mugilidae	*Mugil cephalus*	Bully mullet
Osmeridae	*Thaleichthys pacificus*	Eulachon
Paralichthyidae	*Pseudorhombus cinnamoneus*	Cinnamon flounder
Pomatomidae	*Pomatomus saltatrix*	Tailor
Sciaenidae	*Argyrosomus japonicus*	Mulloway
Sparidae	*Acanthopagrus australis*	Yellowfin bream
Synodontidae	*Saurida* spp.	Lizardfish

Table 2 Location and targeted species in manipulative experiments (chronological order) testing anterior modifications to penaeid trawls ([1]spreading mechanisms, [2]framelines and/or ground gear and [3]trawl bodies; following Fig. 1) for their effects on catches (target and bycatch), habitat impacts and energy intensity (drag or fuel). SR, spread ratio; PE, polyethylene; PA, polyamide; and SMO, stretched mesh opening. Peer-reviewed and grey literature in bold and normal fonts, respectively. *P < 0.05.

Country and species	Anterior modifications tested	Effects on catches	Effects on habitat contact	Effects on energy intensity	Reference
USA (*Penaeus setiferus*)	[1]Single- vs double-rigged otter trawls.	Although not standardised for SR, double rig was expected to increase target catches by 15–30%.	Not assessed, but unlikely to be any differences.	Lower resistance hypothesised, but not quantified.	Knake *et al*. (1958)
USA (*Penaeus aztecus* and *P. duorarum*)	[2]Conventional vs electrical shrimp trawl system (EST).	The EST caught 6 × more *P. aztecus* and *P. duorarum* h^{-1} during diurnal deployments, but 30% less of these species during nocturnal deployments.	Not assessed, but unlikely to be any differences, although if the ground chain was no longer required, habitat impacts could be reduced..	Not assessed, but there would be additional fuel associated with EST operation (electricity generation and possibly extra drag).	**Pease and Seidel (1967)**
USA (*Pandalus jordani*)	[3]Conventional otter trawl vs trawl with anterior separating panels (‘BCF’ trawl).	Although not standardised for SR, the BCF trawl reduced *P. jordani* and teleost catches by up to 66 and 80%.	Not assessed, but unlikely to be any differences.	Not assessed, but additional netting in the BCF would have increased drag and likely reduced SR.	**High *et al.* (1969)**
USA (*P. setiferus*)	[1]Double- vs quad-rigged otter trawls.	Although not standardised for SR, a 25% increase in penaeid catches was expected.	Not assessed, but smaller otter boards were used to spread quad rig, and therefore had less total system contact.	Not assessed, although a lower energy requirement ha^{-1} and $catch^{-1}$ was hypothesised.	**Bullis and Floyd (1972)**
Netherlands (*Crangon crangon*)	[2]Conventional vs electrical beam trawls.	Electrical beam trawl caught 1.2× more commercial-sized *C. crangon.*	Not assessed, but unlikely to be any differences, although electrical ticklers could have had less impact on the seabed.	Not assessed, but there would be additional fuel associated with the EST operation.	**Boonstra and De Groot (1974)**
USA penaeids (*P. aztecus*, *P.*	[3]Conventional otter trawls vs those with vertical separator	Although not standardised for SR, the 89-mm panels had the lowest prawn (9%) and	Not assessed, but unlikely to be any differences.	Not assessed, but additional netting in the separator trawls	**Seidel (1975[$])**

duorarum and *P. setiferus*)	panels (51-, 64-, 76- and 89-mm panels and large-mesh sections in upper panel).	bycatch (64%) loss. The 64-mm panel had the greatest penaeid (37%) and teleost (84%) reduction.		would have increased drag.	
USA (*P. aztecus* and *P. duorarum*)	[2]Conventional vs electrical EST (otter trawls).	From an area seeded with penaeids, the EST caught on average more than the control (~ 35 vs 1% of the marked population).	Not assessed, but unlikely to be any differences.	Not assessed, but unlikely to be any differences, or possibly a slight increase in drag by the EST. However, drag and possibly fuel catch^{-1} would be substantially lower.	**Watson (1976)**
India (*Penaeus* spp.)	[1]Single- vs dual-rigged otter trawls.	Although not standardised for SR, twin rig caught 1.5× more* penaeids, and 37% fewer teleosts.	Not assessed, but two fewer otter boards (and therefore less bottom contact) were used with dual rig.	20% less drag for dual rig.	**Ramarao *et al*. (1977)**
USA (*P. aztecus*)	[3]Conventional vs otter trawl with a V-type vertical separator (Fig. 4a).	Although not standardised for SR, the V-type caught up to 62 and 81% less *P. aztecus* and total bycatch.	Not assessed, but unlikely to be any differences.	Not assessed, but netting in the separator trawls would have increased drag.	**Watson and McVea (1977)**
Germany (*C. crangon*)	[3]Conventional vs trawl with large-mesh funnel and discharge hole for separating *C. crangon* and teleosts.	Although not standardised for SR, the modified trawl reduced teleost catches by up to 80%.	Not assessed, but unlikely to be any differences.	Not assessed, but netting in the separator trawls would have increased drag.	Mohr and Rauck (1979)
USA (*P. aztecus, P. duorarum,* and *P. setiferus*)	[2]Conventional otter trawls vs those with large-mesh panels between the frame lines (forward—over headline and reverse—under fishing line).	Although not standardised for SR, the trawl with the forward panel had 17–45% lower penaeid catches and excluded 75% of turtles. The reverse panel had 0–25% lower penaeid catches and excluded all turtles.	Not assessed, but unlikely to be any differences.	Not assessed, but the treatment trawls possibly had greater drag owing to debris accumulation.	Seidel (1979)
USA (*P. aztecus, P. duorarum* and *P. setiferus*)	[3]Conventional vs three otter trawls with separator panels.	Although not standardised for SR, the modified trawl separated penaeids by 30 and 70% and total bycatch by 51 and 49% in upper and lower sections respectively.	Not assessed, but unlikely to be any differences.	Not assessed, but netting in the separator trawls would have increased drag.	Pearce *et al*. (1989[$])
Australia (*Penaeus*	[3]Multifilament PE vs	Although not standardised for SR, there	Not assessed, but unlikely to be	SR was not calculated, but the	**Sumpton *et al*. (1989)**

spp., *Metapenaeus* spp. and *Metapeneopsis* spp.)	monofilament PA trawl (otter trawls).	were no differences in catches of commercial-sized penaeids, but the PA trawl retained fewer* small penaeids and *Loligo* spp. and more* *Portunus pelagicus*.	any differences.	PA trawl had 0.8–2.7% lower* drag catch^{-1}.	
USA (*P. aztecus* and *P. setiferus*)	[3]Conventional vs otter trawl with a separating panel (Morrison soft TED; Fig. 4b).	Although not standardised for SR, the TED had no significant effect on penaeid catches but reduced* total bycatch by 24%.	Not assessed, but unlikely to be any differences.	Not assessed, but the TED would have increased drag.	**Kendall (1990)**
Australia (*Penaeus plebejus*)	[1]Single rig with, 4 or 140-m sweeps vs triple rig (otter trawls).	No significant effects of treatment trawls on *P. plebejus* weight ha^{-1} trawled, but the single rig with 140-m sweeps caught >2× as many fusiform teleosts.	Not assessed.	Not assessed.	**Andrew *et al*. (1991)**
Brazil (*Xiphopenaeus kroyeri*)	[3]Short (AB side taper) vs long (1N2B) trawl (otter trawls).	Although not standardized for SR, the short trawl caught 5% more penaeids, and 17% less total bycatch.	Not assessed, but unlikely to be any differences.	Not assessed, but the shorter trawl probably had less drag.	Conolly (1992)
Australia (*P. plebejus*)	[3]Conventional vs otter trawl with a Morrison soft TED.	Although not standardised for SR, the TED had no significant effect on *P. plebejus* catches but reduced* total bycatch by 32%.	Not assessed, but unlikely to be any differences.	Not assessed, but the TED would have increased drag.	**Andrew *et al*. (1993)**
USA (*P. setiferus, P. aztecus* and *P. duorarum*)	[1]Skimmer vs otter trawl.	Skimmer trawl caught 6× more **P. setiferus* and 29% less *P. aztecus* and *P. duorarum* and total bycatch min^{-1} trawled.	Not assessed.	The skimmer trawl was estimated to have lower drag.	**Coale *et al*. (1994)**
Australia (*P. plebejus, Metapenaeus bennettae* and *Peneaus esculentus*)	[3]Conventional vs otter trawl with a Morrison soft TED.	Although not standardised for SR, the TED reduced* total penaeids and total bycatch by up to 29 and 32%.	Not assessed, but unlikely to be any differences.	Not assessed, but the TED would have increased drag.	**Robins-Troeger (1994)**
USA (*P. aztecus, P. duorarum* and *P. setiferus*)	[3]High-opening tongue vs low opening (50% less) two-seam trawl (otter trawls).	The high-opening tongue trawl caught more* total, invertebrate and penaeid catch (mostly *P. setiferus*) ha^{-1} trawled.	Not assessed, although the two-seam trawl had a SR of 0.6 vs 0.5 for the high-opening tongue trawl.	Not assessed, but the low-opening trawl probably had less drag.	**Stender and Barnes (1994)**

Australia (*Metapenaeus macleayi*)	[3]Conventional vs otter trawl with funnel-shaped mesh BRD (termed 'blubber-chute').	Although not standardized for SR, the blubber chute caught 15 and 75% fewer* *M. macleayi* and total bycatch.	Not assessed, but unlikely to be any differences.	Not assessed, but the blubber chute probably increased drag.	**Broadhurst and Kennelly (1996)**
Australia (*Peneaus latisulcatus*)	[2]Conventional vs water-jet beam trawls (sampling tools).	Water-jet beam trawl was >3× more effective at catching *P. latisulcatus* m^{-2}.	Not assessed, but possibly lower impacts could be achieved through using jets rather than solid ground gear.	Not assessed, but there would be additional fuel associated with water-pump operation.	**Kangas and Jackson (1998)**
USA (*P. aztecus* and *P. duorarum*)	[2]High-profile (conventional) vs low-profile skimmer trawls.	The low-profile trawl caught less *P. aztecus*, *P. duorarum* and teleosts by 39*, 17 and 14%.	Not assessed, but unlikely to be any differences.	Not assessed, but the high-profile trawl would have more drag.	**Hines *et al*. (1999)**
Japan (*Metapenaeopsis barbata*)	[2]Conventional vs beam trawl modified with a ground-gear panel (termed 'SURF-BRD') designed to direct unwanted catches to a lateral escape exit.	SURF-BRD allowed some juvenile teleosts to escape while maintaining catches of targeted *M. barbata.*	Not assessed, but unlikely to be any differences.	Not assessed, but the greater twine area associated with the SURF-BRD would have increased drag.	**Kajikawa *et al.* (1999)**
Australia (*P. latisulcatus*)	[3]Conventional (45-mm SMO and 1.7-mm twine Ø) vs 53-mm SMO (1.7-mm twine Ø vs 53-mm SMO (1-mm twine Ø) trawls (otter trawls).	Although not standardized for SR, the treatment trawls maintained catches of target-size *P. latisulcatus*, while reducing* undersize individuals (by up to 16%) and total bycatch (by up to 29%).	Not assessed, but unlikely to be any differences.	Not assessed, but at constant SR, the larger-mesh trawls would have had less drag.	**Broadhurst *et al* (2000)**
Mexico (*Peneaus vannamei*, *P. aztecus*, *Peneaus stylirostris* and *Peneaus brevirostris*)	[3]Short (AB) vs long (49% longer) trawls (otter trawls).	Although not standardized for SR, the short trawl caught 15–50% less total bycatch and up to 3% more penaeids than the long trawl.	Not assessed, but unlikely to be any differences.	Not quantified, but the shorter trawl would be expected to have less drag.	**Sarmiento-Nafate *et al*. (2007)**
Australia (*M. macleayi*)	[2]Low (0.8m) vs high (1.2 m) headline heights in otter trawls.	Although not standardised for SR, there was no significant effect on *M. macleayi*, but the higher headline trawl caught > 2× more* *Herklotsichthys castelnaui* and *Gerres subfasciatus*.	Not assessed, but unlikely to be any differences.	Not assessed, but drag for the higher opening trawl would be greater.	**Johnson *et al*. (2008)**

Australia (*M. macleayi*)	[3]Conventional (41-mm SMO and 1.1-mm twine Ø) vs 26-mm SMO (1.1-mm twine Ø) trawl (otter trawls).	Although not standardized for area trawled, there was no difference in *M. macleayi* catches between trawl bodies, but the 26-mm net retained fewer* large *Acanthopagrus australis*.	Not assessed, but unlikely to be any differences.	Not assessed, but the larger-mesh trawls would have had lower drag.	**Rotherham *et al*. (2008)**
Australia (*P. plebejus* and *P. latisulcatus*)	[1, 2]Conventional vs batwing otter boards (Fig. 5b). Conventional vs soft-brush ground gear (otter trawls).	The trawl with batwings caught 90 and 10% less sedentary bycatch and *P. plebejus*, *P. latisulcatus*, respectively. The soft brush caught 12–15 and 35% fewer penaeids and starfish, respectively.	Compared to conventional configurations, the batwing had had 62% less substrate contact. The soft brush has less contact, but this was not quantified.	The soft brush and batwing boards evoked 3.4 and 13% less drag and the batwing was hypothesised to require 20–25% less fuel for the same SR.	Sterling and Eayrs (2008)
Japan (*M. barbata*)	[2]Conventional beam trawls vs one with modified (higher opening) SURF-BRD.	Trawl with SURF–BRD effectively excluded *Saurida* spp. and *Pseudorhombus cinnamoneus*, while maintaining catches of penaeids.	Not assessed, but unlikely to be any differences.	Not assessed, but the greater twine area associated with the SURF-BRD would have increased drag.	**Kajikawa *et al.* (2009)**
Australia (*P. esculentus, P. semisulcatus, Metapenaeus endeavouri* and *Metapenaeus ensis*)	[2]Conventional vs trawl with illuminated headline (otter trawls).	SR was not assessed, but unlikely to be different. Illuminated trawl caught 1.5× more teleosts and, 36% fewer penaeids h^{-1} trawled.	Not assessed, but unlikely to be any differences.	Not assessed, but unlikely to be any differences.	Maynard and Gaston (2010)
Australia (all penaeids)	[3]Conventional PE trawls vs T90 Hampidjan (T90 H) vs Hampidjan (H) vs ultracross (U) vs euroline (E) in a flume tank (otter trawls).	Not assessed.	Not assessed, but unlikely to be any differences.	Compared to the PE (control) the T90H trawl had 12% more drag while the H, U and E trawls had less* drag of 18, 31, and 9% respectively.	Balash and Sterling (2012)
Australia (*M. macleayi*)	[1]Beam vs otter trawl.	Beam trawl caught 33 and 79% fewer* *M. macleayi* and *H. castelnaui* ha^{-1} than the otter trawl.	Beam trawl had 18% less total bottom contact.	Beam had 10% less* drag.	**Broadhurst *et al*. (2012a)**
Australia (*M. macleayi*)	[3]Short (1N5B) two-seam vs short (1N5B) four-seam vs	Catches of *H. castelnaui* ha^{-1} were 66% lower* in the short trawls, but owing to too	Not assessed, but unlikely to be any differences.	Compared to the longer 1N2B trawls, the shorter 1N5B	**Broadhurst *et al*. (2012b)**

	long (1N2B) two-seam vs long (1N2B) four-seam trawl (otter trawls).	large a mesh size (42 mm SMO), catches of *M. macleayi* were also reduced* (by 50%).		designs reduced* drag by 4.3%.	
Australia (*P. esculentus, P. semisulcatus* and *M. endeavouri*)	[2]Conventional vs trawl with illuminated headline (otter trawls).	SR was not assessed, but unlikely to be different. The Illuminated trawl reduced* teleosts by 18.2% and increased penaeid catches by ~6%.	Not assessed, but unlikely to be any differences.	Illuminated trawl expected to be more efficient because of a lower fuel-to-catch ratio.	Gaston *et al.* (2012)
Japan (*M. barbata*)	[2]Two types of SURF-BRDs in beam trawls with forward- and rear-facing guiding panels were compared.	The SURF-BRD with the forward-facing guiding panel had better species contact probability and selectivity.	Not assessed, but unlikely to be any differences.	Not assessed, but unlikely to be any differences.	**Kajikawa *et al.* (2013)**
Australia (*Penaeus* spp.)	[3]High-strength netting in four trawls vs a standard PE trawl.	Improved penaeid catches, but also greater total bycatch in trawls with high-strength netting.	Not assessed, but unlikely to be any differences.	Up to 21% less fuel estimated for high strength netting and matched otter boards in double-rig configuration.	Sterling (2012)
Australia (*M. macleayi*)	[1]Dual- vs double-rigged otter trawls (with long and short bridles).	Dual rig caught 35 and 61% fewer* *M. macleayi* and *Argyrosomus japonicus* ha^{-1} than double rig. Bridle length affected SR, but not catches.	Dual rig had 19−26% less total bottom contact than double rig.	Dual rig had 24% less* drag.	**Broadhurst *et al*. (2013a)**
Australia (*M. macleayi*)	[1]Single- vs double- vs triple- vs quad-rigged otter trawls.	Compared to all other configurations, single rig caught the most* *A. australis* ha^{-1} trawled. There were no differences in *M. macleayi* catches ha^{-1} among configurations.	Triple- and single-rigs had 2−16% less total bottom contact than quad- and double-rigs.	Triple- and quad-rigs had incrementally less* drag than single- and double-rigs (by up to ~11 and 4%).	**Broadhurst *et al*. (2013b)**
India (*Parapenaeopsis stylifera* and *Metapenaeus dobsoni*)	[3]60-mm sieve net vs 50-mm sieve nets in conventional otter trawls.	Although not standardized for SR, the 60- and 50-mm sieve nets caught less penaeids (4.5 and 19.5%) and total bycatch (37 and 33%).	Not assessed, but unlikely to be any differences	Not assessed, but trawls with the sieve nets would have had greater drag.	**Sabu *et al*. (2013)**
Australia (*M. macleayi*)	[3]Short (1N5B) deep wing vs short (1N5B) shallow wing vs	Side taper and wing depth had interactive* and varied effects on catches, but	Not assessed, but unlikely to be any differences.	There were incremental drag reductions* of up to 18%	**Broadhurst *et al*. (2014a)**

	long (1N3B) deep wing vs long (1N3B) shallow wing (all 32 mm SMO) vs a conventional 41-mm SMO trawl (1N3B deep wing) (otter trawls).	compared to the conventional 41-mm trawl, the short shallow-wing design (least twine area) reduced* total teleosts ha^{-1} by 57% with no effect on catches of *M. macleayi*.		associated with reducing twine area via either shorter bodies or shallower wings.	
Australia (*M. macleayi*)	[1]Beam-trawl SR of 0.5 vs 0.6 vs 0.7 vs 0.8.	Incrementally fewer* *M. macleayi* were retained (by up to 51%) ha^{-1} with increasing SR, while the three highest SRs caught fewer teleosts* (by up to 30%) ha^{-1} than the 0.5 SR.	Increasing SR increased ground-gear surface area contact by the stated proportions, but probably with less pressure.	Increasing SR incrementally increased* drag (0.5 SR had 16% lower drag than the 0.8), but less drag when standardised by SR (or SAR).	**Broadhurst *et al*. (2014b)**
USA (*P. setiferus* and *P. aztecus*	[1]Conventonal flat-rectangular vs cambered and otter boards.	The trawls with the cambered boards caught ~3% more *P. setiferus* and *P. aztecus*.	Not assessed, but the cambered otter boards were 50% smaller and therefore had less lateral contact.	The modified configuration required 10–39% less fuel, with most savings attributed to the otter boards.	Haby and Graham (2014)
Australia (*M. macleayi*)	[1]Otter trawl with and without sweeps vs beam trawls (1.25 × larger) with and without a SAFE.	While the otter trawl with sweeps caught more* *M. macleayi* ha^{-1} removing sweeps, using a beam or adding a SAFE reduced* the bycatch of *H. castelnaui* by up to 48%.	Total system contacts among treatments were similar, but the beam trawls had 85% less base-plate contact.	Both beam trawls had up to 31% less* drag than the otter trawls.	**McHugh *et al*. (2014)**
USA (mostly *Tozeuma carolinense* and *P. duorarum*)	[1]Otter vs rollerframe trawls (sampling tools).	The rollerframe caught a greater* amount of individuals of most species ha^{-1}.	No observed impacts for either gear.	Not assessed, but the rollerframe should have had less drag.	**Stallings *et al.* (2014)**
Australia (*Metapenaeus insolitus, M bennettae, P. esculentus* and *P. semisulcatus*)	[3]Double crown and bosom (‘W’) otter trawl vs conventional trawl tested in flume tank and at sea.	The W trawl caught more penaeids ha^{-1} but less total bycatch.	Not assessed, but the W trawl required much smaller otter boards than the double rig.	W trawl had 20%* less drag than the conventional trawl when tested at sea, which was similar to the flume tank estimation.	**Balash *et al.* (2015a)**
Australia (all penaeids)	[3]W and conventional trawl, with T0 body and T45 side panels vs W and conventional	Not assessed.	Not assessed, but unlikely to be any differences.	Orientation of the mesh direction to water flow did not have any practical effect on	**Balash *et al.* (2015b)**

	trawl, with T45 body and T0 side panels vs conventional trawl with T0 body and T0 side panels tested in a flume tank.			drag. The W trawl cases had 8.3% less overall predicted drag (including an estimate of otter board drag) than the conventional trawl. Greater benefits were expected in the field with commercial trawls.	
Australia (all penaeids)	[1]One battened batwing sail under various AOAs and with five combinations of twist and camber in a flume tank.	Not assessed.	Not assessed, but the batwing would have up to 90% less bottom contact than conventional otter boards.	A 20^{o} AOA and with medium twist and camber should provide up to 20% drag savings for double rig.	Balash *et al*. (2015c)
Australia (all penaeids)	[1]Battened vs high-rake batwing sails under various AOA and with five combinations of twist and camber in a flume tank.	Not assessed.	Not assessed, but the batwing would have up to 90% less bottom contact than conventional otter boards.	A 20^{o} AOA was a good operating condition for all combinations, and best performance (highest efficiency with acceptable stability) was achieved with high twist and low camber for the high-rake sail and medium twist and camber for the battened sail.	**Balash *et al*. (2015d)**
Australia (*P. plebejus* and *M. macleayi*)	[1]Batwing vs flat-rectangular otter boards, with and without a restraining wire (SAFE).	Otter boards had no effect on *P. plebejus* catches ha^{-1} trawled, but the restrained trawls caught up to 19% less* bycatch than those spread conventionally, or by the batwings.	Compared to the conventional otter boards, the batwing and restrained configuration had 88 and 40% less bottom contact.	Compared to the other configurations, the batwing had 5% less* drag, but some of this was explained by a confounding effect of different SRs.	**Broadhurst *et al*. (2015a)**
Australia (*M. macleayi*)	[2]Soft-brush vs 6-mm, vs 8-mm, vs 10-mm chain ground gears (beam trawl; Fig. 3b).	Ground gear had no effect on catches of *M. macleayi* ha^{-1} but 45% fewer* *Arius graeffei* were caught by trawls with the 6-mm chain than the 10-mm or soft brush.	The soft brush had 63% less linear bottom contact than the conventional ground gears.	Ground gears accounted for between 15 and 22% of the total tested system drag, and their modification in conventional systems could	**Broadhurst *et al*. (2015b)**

				reduce drag by ~5%.	
Australia (*M. macleayi*)	[3]Tightly-hung frame line with diamond- or square-mesh wings vs loosely-hung frame line with diamond- or square-mesh wings (all short otter trawls with 35 mm SMO) vs a long conventional 41-mm trawl.	Compared to the conventional 41-mm trawl, all shorter, smaller-meshed trawls caught fewer* teleosts ha^{-1}, while the trawls with the square-mesh wings reduced* the catches of undersize *M. macleayi* ha^{-1} by 54−72%.	Not assessed, but unlikely to be any differences.	Compared to the conventional trawl, all four shorter small-meshed designs had lower* drag by up to 12%.	**Broadhurst *et al*. (2015c)**
Australia (*M. macleayi*)	[3]Short (1N5B) vs long (1N3B) trawl(35 mm SMO) otter trawls during variable ambient light	The short trawl consistently caught fewer* undersize *M. macleayi* ha^{-1} but only reduced* catches of *H. castelnaui* (by up to 40%) when there was sufficient ambient light.	Not assessed, but unlikely to be any differences.	Not assessed, but the shorter trawl would have had less drag.	**Broadhurst *et al*. (2015d)**
USA (*P. jordani*)	[2]Conventional otter trawl vs one with illuminated footrope.	The illuminated footrope reduced* catches of *Thaleichthys pacificus* by 91% and other teleosts by 56–82%, and with no significant effect on *P. jordani* catches.	Not assessed, but unlikely to be any differences.	Not assessed, but unlikely to be any differences.	**Hannah *et al*. (2015[$])**
India (*P. stylifera* and *M. dobsoni*)	[3]Conventional vs trawl with a horizontal separator panel assessed.	Although not standardized for SR, the lower section caught more* (kg h^{-1}) of *P. stylifera*, *M. dobsoni* and benthic teleosts than the upper section.	Not assessed, but unlikely to be any differences.	Not assessed, but the separator trawl would have had more drag.	**Madhu *et al*. (2015)**
Australia (*M. macleayi*)	[1]Beam and otter trawls with and without various SAFEs.	All SAFES maintained target catches of *M. macleayi* ha^{-1} , but reduced* total bycatch by up to 51% and *Pomatomus saltatrix, Mugil cephalus* and *H. castelnaui* by up to 58%.	Not assessed, but unlikely to be any differences.	No effects.	**McHugh *et al*. (2015a)**

Australia (*M. macleayi*)	[1]Batwing vs flat-rectangular otter boards.	The batwing displaced fewer* *M. macleayi* and *Arenigobius bifrenatus* (by 78 and 25%).	The batwing displaced 89% fewer* shells (*Anadara trapezia* and *Spisula trigonella*) and damaged proportionally* less.	Not assessed, but the batwing would have had less drag.	**McHugh *et al*. (2015b)**
Australia (*M. macleayi*)	[1]Batwing vs flat-rectangular vs kilfoil vs cambered otter boards.	Trawls spread by the cambered otter boards retained up to 13% more* *M. macleayi* ha^{-1} than the other treatments, but otter boards had no effects on bycatches.	Compared to the three other designs, the batwing had 86% less bottom contact.	Compared to the three other designs, the batwing had 18% less* drag.	**McHugh *et al*. (2015c)**

[$]Only those modifications assessed in posterior sections were included

Captions to figures

Fig. 1. Three-dimensional drawing of (a) beam and (b) otter trawls and (c) mechanical-type BRD and square-mesh codend with key terminology.

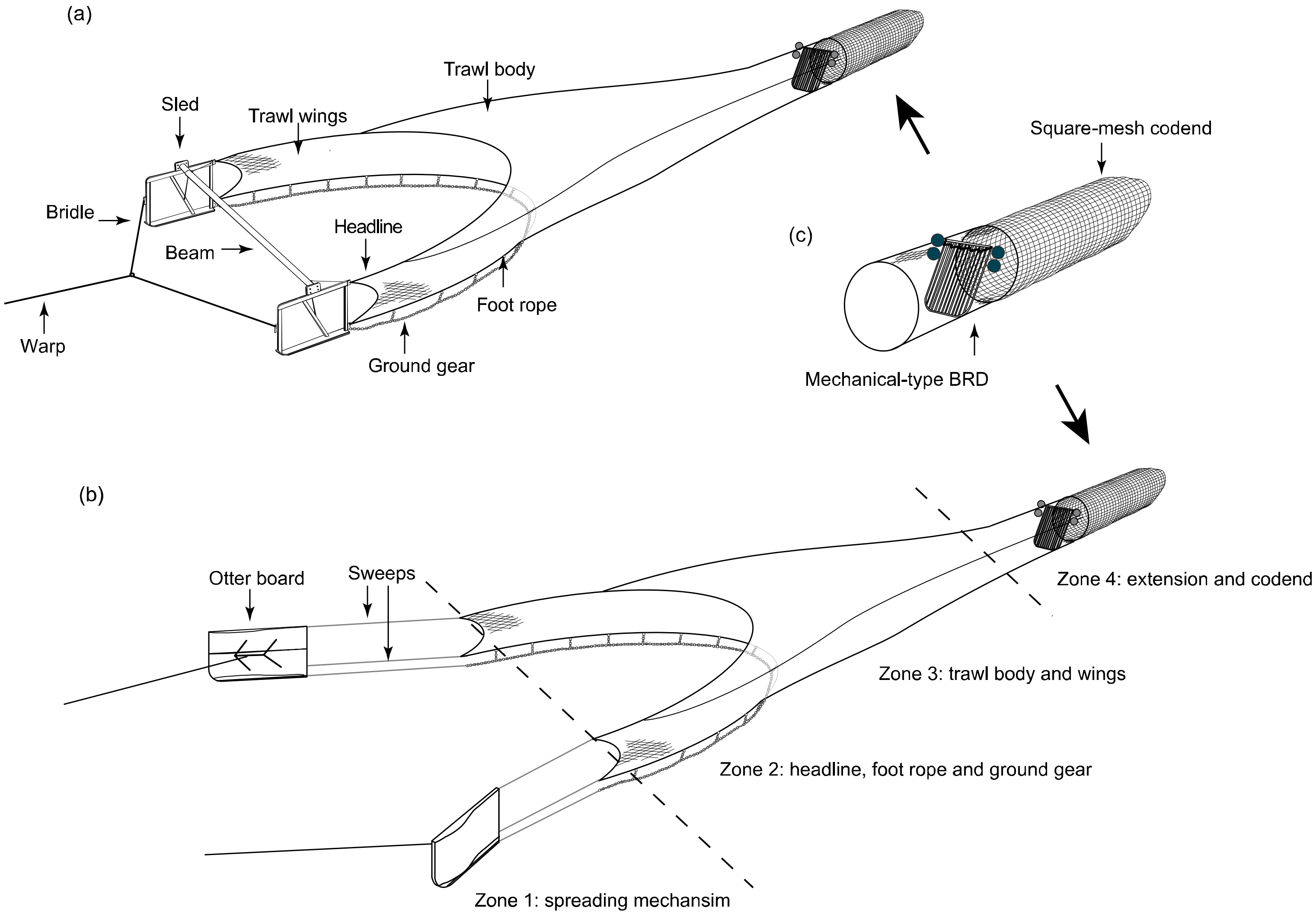
Fig. 2. A diagrammatic representation of generic (a) single-, (b) double-, (c) dual-, (d) triple-, (e) quad-, and (f) penta-rigged otter trawls, and (g) single-, and (h) double-rigged beam trawls; and (i) a skimmer trawl. Superscript numbers represent [1]otter board, [2]sled, [3]beam and [4]weight. Trawls in multi-configurations are scaled from a single rig (e.g. double- and dual-rigs are 50% of single rig).

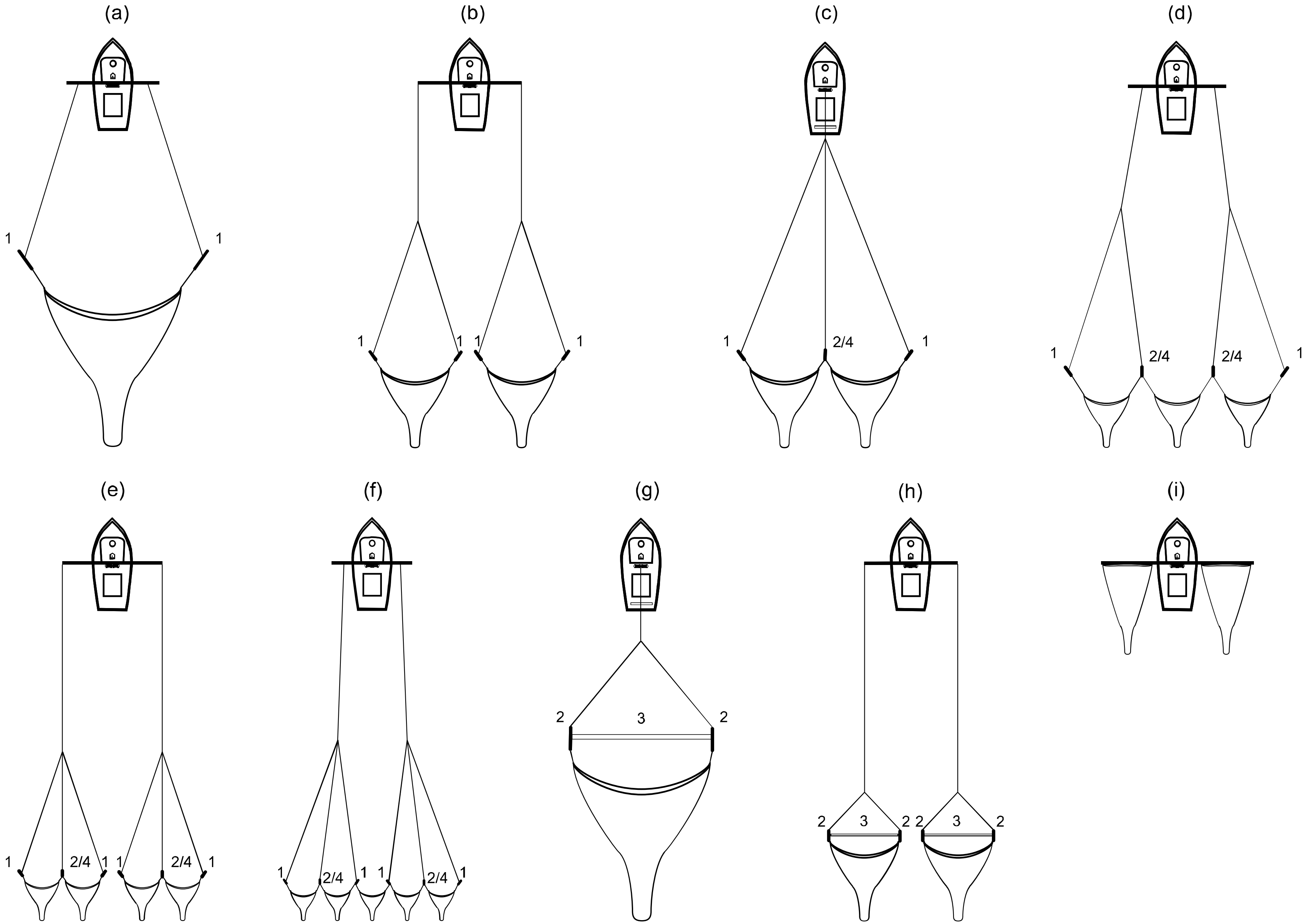
Fig. 3. Front view of (a) conventional chain, (b) soft-brush, and (c) hydrorig ground gears.

Fig. 4. The (a) V-type separator and (b) Morrison soft TED in a generic penaeid trawl.

Fig. 5. Diagram of (a) conventional and (b) batwing otter boards.

Fig. 6. A proposed protocol for reducing the environmental impacts of penaeid trawls.


(a)
Trawl body
Sled
Trawl wings
Square-mesh codend
Bridle
Headline
(c)
Beam
Foot rope
Warp
Ground gear
Mechanical-type BRD
(b)
Otter board
Sweeps
Zone 4: extension and codend
Zone 3: trawl body and wings
Zone 2: headline, foot rope and ground gear
Zone 1: spreading mechansim


(a)
1
1
(b)
1
1
1
1
(c)
1
2/4
1
(d)
1
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2/4
1
(e)
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(f)
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2/4
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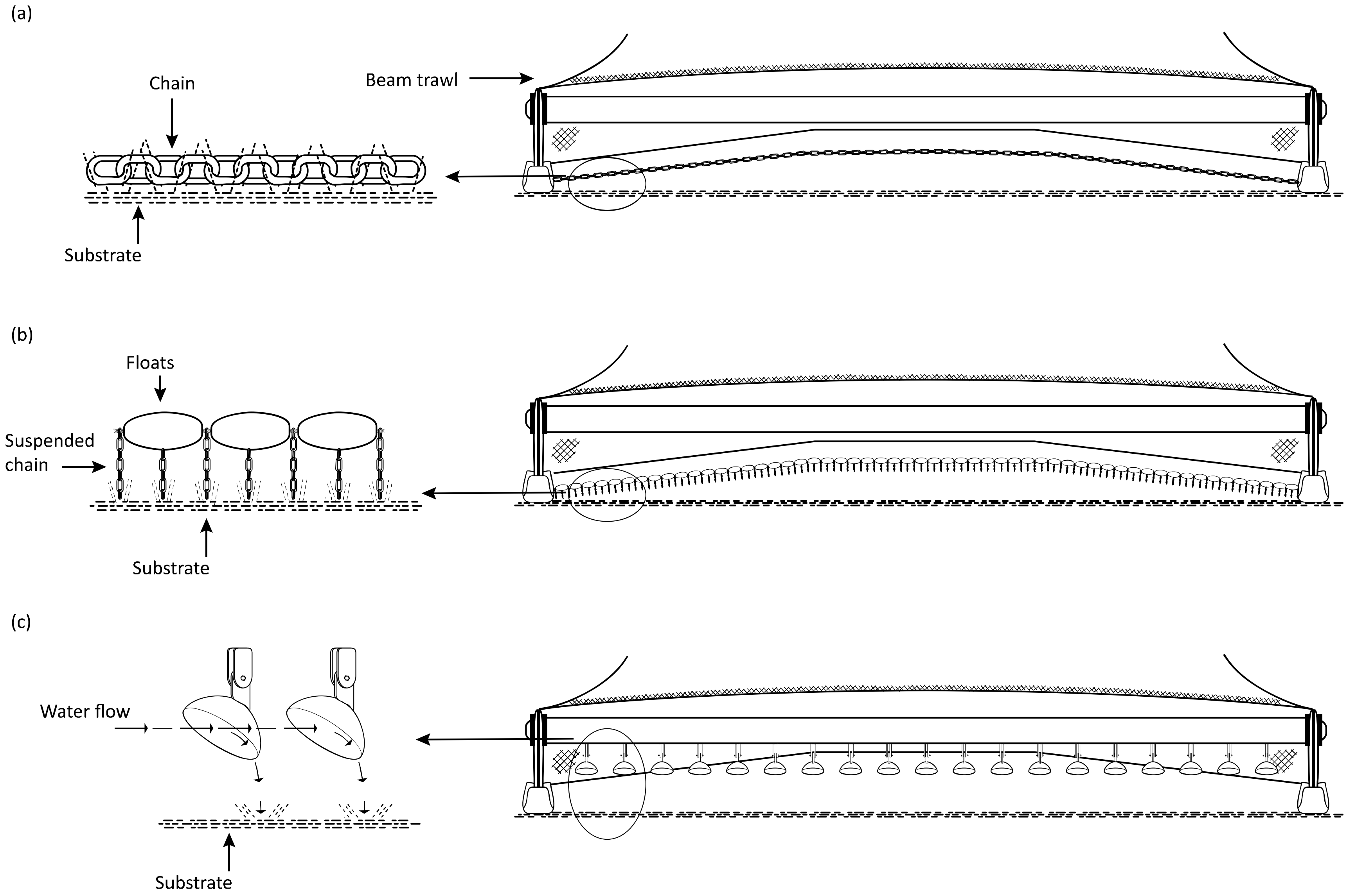
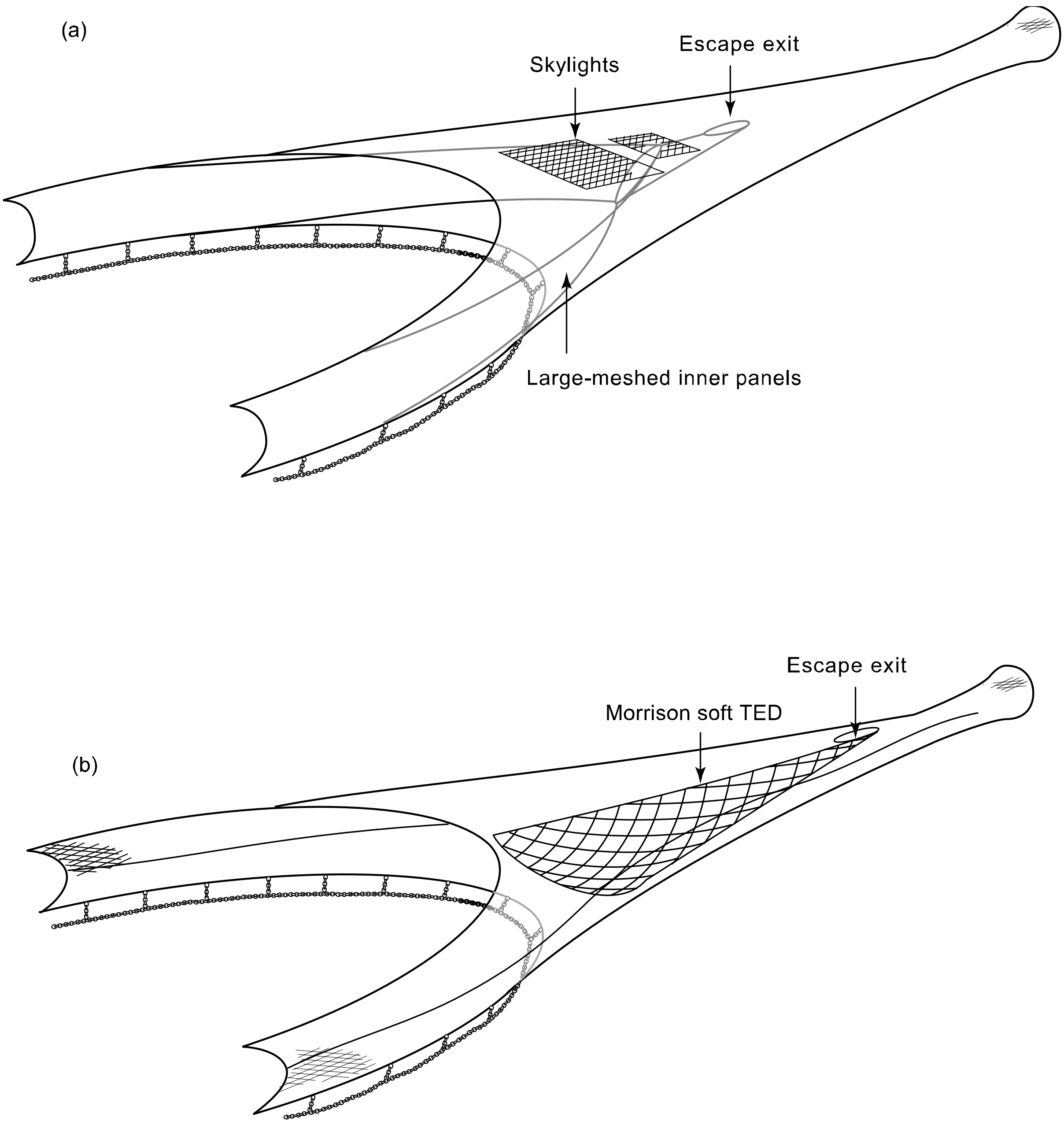
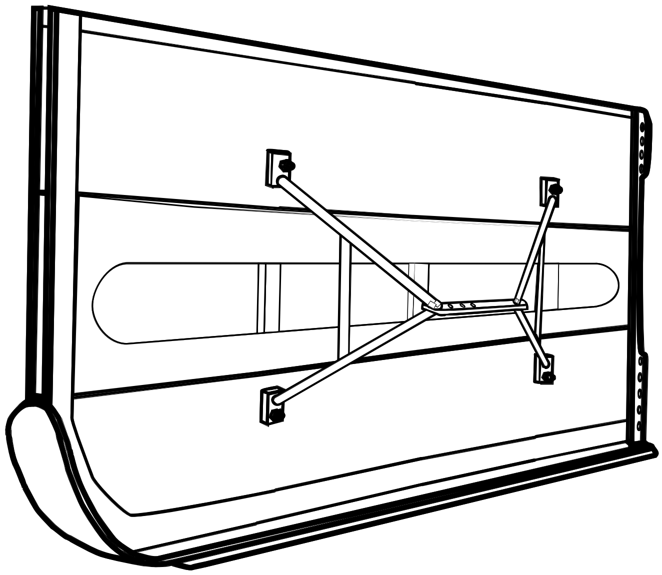
(g)
2
3
2
(h)
2
3
2
2
3
2
(i)

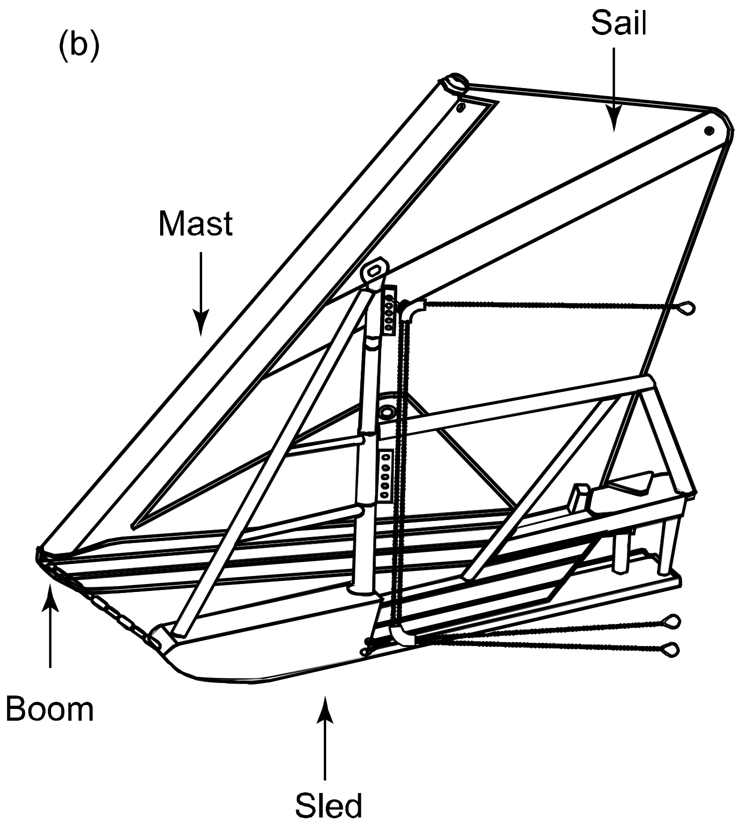

(a)
Chain
Beam trawl
Substrate
(b)
Floats
Suspended chain
Substrate
(c)
Water flow
Substrate


(a)
Skylights
Escape exit
Large-meshed inner panels
(b)
Escape exit
Morrison soft TED

(a)



(b)



Protocol

1). Select the most appropriate multi-trawl configuration

- Choose a conventional configuration with a bias towards sleds, including: a single beam, or triple- or quad-rigged otter trawls.
- Explore the potential for installing SAFEs between spreading mechanisms.
- Explore the utility of low-impact ground gears.

2). Reduce otter-board angle of attack (AOA) to ~20^{o}

- Choose conventional configurations with the lowest stable operating AOA.
- Explore the potential of retrofitted modifications to existing designs for reducing AOA.
- Explore the potential for novel designs like the batwing otter board.

3). Minimise twine area

- Optimise mesh size and twine diameter for the targeted organisms and then reduce trawl body to the shortest practical length by maximising side taper and minimising wing height.
- Explore the potentail for increasing lateral mesh openings at strategic positions, via T45 or T90 panels, as a means for reducing unwanted catches.
- Explore the potentail for minimising twine area via alternative trawl designs like tongue or W-trawls and/or high-order multi rigs.

4). Optimise spread ratio (SR)

- Optimise the SR within a defined range for the desired trawl system.

Appendix 2. McHugh, M. J., Broadhurst, M. K., Sterling, D. J. and Millar, R. B. (2014) Comparing and modifying penaeid beam- and otter-trawls to improve ecological efficiencies. *Fisheries Management and Ecology* **21**: 299–311

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Comparing and modifying penaeid beam- and otter-trawls to improve ecological efficiencies

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Abstract

In an attempt to improve the selectivity and engineering performances of generic penaeid trawls, three established and one novel spreading-mechanism configuration were assessed: otter boards attached (i) with and (ii) without 3.15-m sweeps to a 7.35-m headline trawl, and a beam rigged directly to a 9.19-m trawl (iii) with and (iv) without a horizontal wire and plastic streamers. Despite more surface area (7.5 vs 6.0 m^2) both beam-trawl configurations had significantly lower drag than the otter trawls (≤30%). When catches were standardized to per ha, the otter trawl with sweeps retained significantly more (1.3 to 2.4 times) school prawns, *Metapenaeus macleayi* (Haswell) than the other three configurations. Within systems, removing sweeps or adding a horizontal wire significantly reduced the unwanted catches of a key teleost (southern herring, *Herklotsichthys castelnaui,* Ogilby) by 41 and 48%. The results illustrate the utility of simple anterior modifications for independently addressing penaeid-trawling environmental issues.

Keywords: penaeids, bycatch reduction; modifications; otter trawls; beam trawls; drag

Introduction

Mobile demersal fishing gears, including beam and otter trawls, are among the most commonly used commercial methods; accounting for ~25% of the total global catch or ~15% of all marine fish and >80% of shrimp/prawn catches (Kelleher 2005; Watson *et al.* 2006). While their contribution towards global harvests is important, demersal trawls and especially those targeting penaeids often are associated with poor size and species selectivity (Kelleher 2005) and indirect (e.g. predator removal) effects on epifauna and infauna (Kaiser *et al.* 2002). Such impacts cause varying levels of unaccounted fishing mortality, and can have negative consequences for key stocks and habitats (Broadhurst *et al.* 2006). Demersal trawling also requires large amounts of fuel, often representing up to 30% of an operator's total costs (Thomas *et al.* 2010).

Historical recognition of the above ecological and economic issues has led to the investigation of resolution strategies; mostly via isolated attempts at improving size and species selection using retrospectively-fitted bycatch reduction devices in penaeid (e.g. Broadhurst 2000) and fish trawls (e.g. Jennings & Revill 2007) and proposing alternatives that reduce benthic impacts (Kaiser *et al.* 2002; Kennelly & Broadhurst 2002). Recently, improved fuel efficiencies have been achieved through better vessel engineering (e.g. hull design or propulsion systems; Thomas *et al.* 2010), trawl designs and operation (i.e. reduced towing and steaming speeds) (Parente *et al.* 2008). Although clearly validated improvements, many of these modifications require large capital investment and have rarely been implemented without legislation (Jennings & Revill 2007).

It is well-established that to successfully develop and introduce new fishing techniques to improve sustainability, there is a need to incorporate the fishers' perspective in the subsequent design and/or testing (Kennelly & Broadhurst 2002). Fishers are more likely to use new techniques if they perceive realised benefits, and there is limited capital investment (Jennings & Revill 2007). Applying cheap methods to improve sustainability is especially pertinent for small-scale/artisanal fisheries like penaeid otter trawling because they are associated with the greatest bycatch rates (Kelleher 2005). One possible alternative for improving species selection in some such fisheries is to simply substitute the otter boards for a lightweight beam; the presence of which can produce sufficient stimuli to direct some swimming fish away from the mouth of the trawl (Broadhurst *et al.* 2012). Equally important, a beam should also reduce both drag and seabed-habitat impacts—owing to relatively less contact by the parallel sleds (Broadhurst *et al.* 2012).

However, one potential issue for fishers associated with removing otter boards from penaeid-trawl systems is that any reduction in substrate penetration (and therefore 'total-system contact'), could result in fewer penaeids being dislodged and herded into the trawl (e.g. Broadhurst *et al.* 2012, 2014). It may be possible to address this issue by increasing the trawl footrope length, which can be justified from an environmental point of view because it is generally accepted that otter boards inflict relatively more habitat damage (Gilkinson *et al.* 1998). It is also possible that despite some increase in footrope length and the inclusion of a beam and two sleds, the system could still have relatively lower drag than using a smaller trawl with otter boards (since otter boards can contribute up to 40% of the total drag of some configurations; Sterling 2000), although the boundaries of such a relationship remain unknown.

Irrespective of the spreading mechanism, it may also be possible to also improve the size and especially species selectivity of penaeid trawls via simple modifications within existing configurations. For example, because it is well established that sweep wires (between the spreading mechanism and the trawl; Figure 1a) can herd fish inwards (e.g. Engås & Godø 1989; Andrew *et al.* 1991) their removal could reduce catches. Additionally, like a rigid beam and as suggested by Broadhurst *et al*. (2012) horizontal vibrating wires and/or obstructions across the mouth of the trawl might herd fish away, either via visual or tactile responses (e.g. Main & Sangster 1983). Fish are known to respond to both visual and auditory stimuli (Ladich & Fay 2012), but there is a paucity of research exploiting such behaviour to promote their avoidance of penaeid trawls. Such research is important, since intuitively, modifications that facilitate avoidance are likely to be associated with lower unaccounted fishing mortality than those that promote escape from the codend (Broadhurst *et al.* 2006).

Considering the above, the aims of this study were to investigate the potential for simple within and between system modifications for improving the ecological efficiency of small penaeid trawls. Specifically, we sought to compare (i) the relative catching and engineering performances of trawls spread by either otter boards or a beam and concurrently (ii) the effectiveness of the presence or absence of sweep wires for the otter trawl and a novel modification involving a horizontal wire across the mouth of the beam trawl. To more closely standardise total-system contacts (i.e. accounting for the loss of substrate penetration by the otter boards), the footrope lengths of the beam trawls were increased. The work was done in Australia, but the results have broader implications among national and international small-scale penaeid-trawl fisheries.

Material and methods

Fishing vessel, monitoring equipment and tested treatments

The experiment was completed in the Lake Wooloweyah estuary (29° 26’S 153° 22’E; sand and mud substrata ~ 1–2 m depth) during summer 2013 using a 10-m double-rigged trawler (104-kw). The trawler had 40-m bridles (6-mm diameter–Ø stainless-steel wire) on a two-drum hydraulic winch, and was equipped with: a global positioning system (GPS; Lowrance, HDS5) to record speed over the ground (SOG in ms^{-1}); fuel monitor (Floscan series 9000); sum log (model: Bronze + Log) to record speed through the water (STW in ms^{-1}); and attachable load cells (Amalgamated Instrument Company; model no. PA6139) to measure the combined tension (kgf) in the paired bridles, which were always deployed to 12 m. Where required (see below) replicate measures of the wing-end spreads of relevant trawls were obtained using Notus paired wireless sensors. The data from the sensors were received through an omnidirectional hydrophone and logged onto a laptop. All electronic data were recorded every 60 s.

Two identical beam assemblies (each 108 kg) were built; each comprising an aluminium yacht mast (6.00 m long × 0.14 m wide × 0.08 m deep) and galvanized-steel sleds (1.07 m long × 0.76 m high × 0.10 m base plates; Figure 1b). The beam length was based on the maximum considered operationally practical by the fisher. Two pairs of cambered, stainless-steel otter boards (each 1.07 m long × 0.76 m high × 54 kg in air total weight) were also constructed. A beam configuration and pair of otter boards were assigned to one side of the trawler throughout the experiment.

Four trawl bodies—two each of 7.35-m (labelled A and B) and 9.19-m (C and D) headline and footrope lengths—were constructed from the same nominal 42-mm (stretched mesh opening−SMO) mesh (identical 1.25-mm Ø twisted polyethylene−PE twine) for use with the paired otter boards and each beam, respectively (Figure 2). All trawls had a posterior circumference of 150 transversals (T) (50 T for the top and bottom panels and 25 T for each side panels; Figure 2). The headline length of the beam trawl was calculated based on a hypothesised spread ratio (proportion of wing-end spread to headline length) of 0.65 for the otter trawl−derived from a model proposed by Sterling (2000). All trawl bodies were rigged with identical Nordmøre-grids (28-mm bar spacing) in extension sections comprising nominal 40-mm PE mesh (2.50-mm Ø twisted twine) and square-mesh codends made from nominal 27-mm polyamide mesh (1.25-mm Ø twine) hung on the bar (see Broadhurst *et al.* 2012 for specifications). The twine areas were 4.80 and 6.38 m^2 for each trawl (comprising body, extension and codend) attached to the otter boards and beam, respectively. Total system areas were calculated as the sum of the twine, ground-chain, sweep wires (if present), frame lines, catch (0.23 m^2) and either the otter boards (× 2) or the beam-and-sled areas, and were 6.99 and 7.48 m^2 for each otter- and beam-trawl configuration.

Experimental design

Prior to starting the work, the four trawl bodies, extensions and codends were checked for mesh uniformity by measuring 15 replicate SMOs using a local, purpose-built gauge. In total, four treatments (two within each spreading mechanism) were deployed in four-day blocks (with replicate 40-min deployments for each treatment) over 12 days. The treatments included the otter trawls (i) with and (ii) without three sweep wires (each 6-mm Ø stainless-steel wire and 3.15 m long between each otter board and wing-end; Figure 1a, c and d); and the beam trawls (iii) with and (iv) without a horizontally strung 1.50-mm Ø stainless-steel wire. We hypothesised that adding the horizontal wire would evoke an escape response among fish and removing the sweep wires would herd fewer fish into the net (Figure 1b-e). The horizontal wire was attached to the centre of the sleds 0.35 m below the 6-m beam and in front of the trawls (Figure 1b). Secured to the wire (0.40 m apart) using swivels were flat strips of green polypropylene (200 mm long × 60 mm wide × 1 mm thick) (Figure 1b).

On each day, one of the above four spreading-mechanism treatments was assigned to a side of the vessel where it remained. One of the two designated trawls within each spreading mechanism was then attached and deployed either three times (on the beam), or two or four times (on the otter boards) after which trawls (within spreading mechanisms) were swapped. The pairs of the Notus sensors were randomly assigned to the A and B otter trawls for two consecutive deployments, before being swapped. Throughout the experiment, each pair of Notus sensors was used 36 times (18 times on each trawl). Load cells were assigned to each Notus-sensor pair and followed their sampling order on the otter trawls, and were similarly rotated among the beam-trawl deployments.

At the end of each deployment, the two codends were simultaneously emptied onto a partitioned tray and the catches separated, with the total weights of penaeids and bycatch recorded along with the numbers or weights (see below) of each bycatch species for each trawl. Total lengths (TL to the nearest 0.5 cm) of the most abundant teleosts were also recorded. A random sample of ~500 g of penaeids was collected and then separated by species in the laboratory. Numbers and weights were recorded and ~100 individuals of the most abundant species (school prawns, *Metapenaeus macleayi* (Haswell) —see Results) were measured for their carapace lengths (CL to the nearest 1 mm). These data were used to estimate the totals (numbers and weights) of each penaeid species in each deployment for *M. macleayi*. In addition to the living bycatch, all debris were recorded by weight.

Data analyses

To confirm the homogeneity of the four trawls the hypothesis of no differences in the SMOs of the various trawls, extensions and codends was tested in a linear model (LM). The remaining biological and technical data collected during fishing were analysed to test the general assumption of no differences among the four spreading-mechanism treatments, but in different formats. For each deployment, the numbers and weights of catches were treated in their unstandardized form (i.e. per 40-min deployment), and also after being standardised to per ha trawled using the area of footrope contact (i.e. average wing-end spread × the distance trawled).

Additionally, in an attempt to explain variability among the numbers and weights of *M. macleayi* between the beam and otter trawls (see Results), the latter data were also standardised to the total-system contact area ((i.e. average wing-end spread + span of otter-board contact) × the distance trawled), where the span of each otter-board contact was calculated by multiplying the otter-board length (1.07 m) by the sine of the angle of attack (AOA; calculated from the predicted wing-end spread of each configuration and using the model proposed by Sterling (2000). This is a deterministic model of trawl performance that will always produce the same output from a given starting condition. Because the sweep wires were above the substratum, they were not included in total system contact (Figure 1a). Similarly, the relatively thin (0.10 m) sled-base plates of the beams were outside the wing-ends and parallel to the tow direction, and so for these configurations the footrope and total-system contacts were considered synonymous (Figure 1e).

All (i) unstandardised and standardised catch data using the (ii) footrope and (iii) total-system contacts of the various configurations were then log-transformed to account for an assumed multiplicative relationship with causal factors, and analysed in separate linear mixed models (LMMs), with the fixed effect of 'spreading-mechanism configuration' and appropriate random factors ('days', 'trawls', 'deployments' × days, and 'sides' of the vessel). Other biological data, including the mean CL of *M. macleayi* and replicate drag per deployment were analysed untransformed. Engineering data, including the area trawled, wing-end spread for the otter trawls, spread ratio and drag were also analysed untransformed, and with appropriate covariates, including SOG and STW, and a variable termed 'current' created by the difference between the two. The models were fitted using the lmer function from the lme4 package in R 2.15.3 (The R Project for Statistical Computing; http://www.r-project.org/) and the significance of trawl configuration determined using a likelihood ratio test (LRT). Any significant differences detected for spreading-mechanism configuration were subsequently explored using pairwise comparisons in conjunction with the Benjamini–Hochberg–Yekutieli procedure to control the false discovery rate (FDR; Benjamini & Yekutieli 2001).

Predicted means from the LMMs for drag were used to calculate relative fuel consumption associated with towing the four treatments. Specifically, assuming that for any given towing speed, the concomitant fuel usage was proportional to the drag, it is possible to determine the relative fuel consumption rate. Fuel consumption was standardised to per ha trawled and per kg of *M. macleayi* caught for each trawl design by comparing the predicted fuel consumption rate with predicted mean wing-end spread (the rate at which area was being swept for a given trawl speed), and the predicted mean absolute (per 40-min deployment) *M. macleayi* catches from the respective LMMs.

Results

Over 12 days, 36 deployments of each spreading-mechanism configuration were completed, catching ~519 and 132 kg of penaeids (nearly all were *M. macleayi*) and fish bycatch, respectively (Table 1). The bycatch comprised 40 species, although more than 89% of the total included southern herring, *Herklotsichthys castelnaui* (Ogilby) (5.0–18.5 cm TL; 46.3%), yellowfin bream, *Acanthopagrus* *australis* (Owen) (4.0–24.5 cm TL; 12.3%), tailor, *Pomatomus saltatrix* (L) (2.5–15.0 cm TL; 10.1%), Ramsey's perchlet, *Ambassis marianus* (Günther) (3.0–11.0 cm TL; 8.9%), silver biddy, *Gerres subfasciatus* (Cuvier) (3.0–14.5 cm TL; 6.8%), and Australian anchovy, *Engraulis australis* (White) (3.0–9.0 cm TL; 4.9%) (Table 1). Blue blubber jellyfish, *Catostylus mosaicus* (Quoy & Gaimard) was also common (Table 1), while debris were restricted to empty shells of *Anadara trapezia* (Deshayes) and *Spisula trigonella* (Lamarck) (~101 kg total). Analyses of catch data were limited to the variables above, and only those of interest were graphed.

In addition to shells, the wing-end meshes of the trawls without sweep wires accumulated more sediment than the other three configurations. These clogged meshes formed an approx. right-angle triangle with a base extending ~2.5 m along the footrope.

Engineering performances

The SMOs were not significantly different between trawls, extensions or codends, with overall means ± SE of 41.25 ± 0.08, 41.40 ± 0.17, and 27.35 ± 0.10 mm, respectively (LM, $p > 0.05$). There was a significant effect of spreading-mechanism configuration on wing-end spread that manifested as a significantly greater spread ratio (SR) for the otter trawl without sweep wires (0.71 ± 0.01; or a predicted mean of 5.25 ± 0.04 m) than with sweep wires (0.67 ± 0.01 or 4.96 ± 0.04 m) and, irrespective of sweep wires, both otter-trawl configurations were spread at significantly greater ratios than the beam trawl (both 0.65 ± 0.00 or 6.00 ± 0.00 m, LMM and FDR, $p < 0.05$; Tables 2−4). Within the otter-board configurations, the absence of sweep wires increased the AOA by 3° (Tables 3).

Drag was also significantly affected by spreading-mechanism configuration, although in addition to the random variables assessed above for wing-end spread the parsimonious model also included SOG, which presented as a positive relationship irrespective of configuration (LMM, $p < 0.001$, Table 2). Predicted mean drags for spreading-mechanism configuration are presented at the centred value of SOG (ms^{-1}), that were derived from the range of logged data for the otter trawl with (0.93–1.95 ms^{-1}) and without sweep wires (0.77–1.95 ms^{-1}) and the beam trawl with (0.93–1.95 ms^{-1}) and without (0.77–1.80 ms^{-1}) a horizontal wire. Compared to both otter-trawl configurations, the beam trawls had significantly lower drags (predicted means reduced by 27–31%; FDR, $p < 0.001$; Tables 3 and 4). In terms of fuel, this equated to ~2.8 and ~2.2 L ha^{-1} for footrope and total-system contacts respectively for both otter-trawl configurations, with the beam trawls using ~1.8 L ha^{-1} for footrope/total-system contacts (Table 3).

Catching performances

Spreading-mechanism configuration significantly affected the catches of *M. macleayi* and their sizes, fish bycatch, *H. castelnaui* and empty shells across all categories (i.e. per 40-min deployment and ha trawled) and the weight of *C. mosaicus* per 40-min deployment (LMM, $p < 0.05$; Tables 2 and 4, Figures 3a and b and 4a−d). Subsequent FDR pair-wise comparisons revealed that in terms of catches per 40-min deployment, both otter-trawl configurations caught the same quantities of *M. macleayi* ($p > 0.05$) but significantly more (predicted mean increases of up to double) than the beam-trawl configurations ($p < 0.05$; Figure 3a and b). Further, within beam-trawl configurations, the presence of the horizontal wire was associated with a significant reduction in catches of *M. macleayi* (by 21%; FDRs, $p < 0.05$; Figure 3a and b). These differences were maintained for standardised catches, except that the otter trawl with sweep wires caught significantly more *M. macleayi* than without for both footrope and total-system contacts (by up to 29%; FDRs, $p < 0.05$; Figure 3a and b). In terms of *M. macleayi* sizes, the beam trawl with the horizontal wire caught significantly larger CLs (by up to 0.5 mm) than the otter trawl without sweep wires (FDR, $p < 0.05$), but there were no other pairwise differences (FDRs, $p > 0.05$; Figure 4). Both the otter trawl with sweep wires and the beam trawl without the horizontal wire had similar fuel intensities for *M. macleayi* (at ~1.0 L kg^{-1}), while the otter trawl without sweep wires and the beam trawl with the horizontal wire operated at 1.2 and 1.3 L kg^{-1}, respectively (Table 3).

The FDR pair-wise comparisons for fish bycatch showed that the otter trawl with sweep wires caught a significantly greater weight (1.6–2.0 times) per 40-min deployment, and number (up to 2.0 times) and weight (up to 2.4 times) per ha of footrope contact, than the other three spreading-mechanism configurations ($p < 0.01$; Figure 5a and c). By comparison, for the number of fish bycatch per 40-min deployment, the otter trawl with sweep wires similarly caught significantly more (by up to 1.6 times) than the otter trawl without sweep wires and the beam trawl with the horizontal wire (FDR, $p < 0.01$), but not the beam trawl without the horizontal wire (FDR, $p > 0.05$; Figure 5c).

For the most abundant fish species, *H. castelnaui*, compared to all other spreading-mechanism configurations, the beam trawl with the horizontal wire retained significantly fewer per 40-min deployment (predicted means reduced by 47–69%) and per ha of footrope contact (by 49–75%, FDR, $p < 0.01$; Figure 5d). The predicted mean numbers of other abundant fish, including *P. saltatrix* and *A. australi*s, were not significantly different among spreading-mechanism configurations (LMM, $p > 0.05$; Figure 5e and f). By comparison, both beam-trawl configurations retained significantly greater weights (1.7 times) of *C. mosaicus* per 40-min deployment than the otter trawls (FDR, $p < 0.01$), but no significant differences were detected for standardised catches (FDR, $p > 0.05$; Figure 5b). The otter trawl without sweep wires retained significantly more shells (99%) than the other three configurations for both per 40-min deployment and standardised catches (FDR, $p < 0.001$).

Discussion

The results from this study reiterate the utility of modifying penaeid-trawl anterior sections for improving their ecological efficiencies measured here as reductions in bycatch and drag, and therefore the fuel rate and intensity (Sumpton *et al.* 1989; Broadhurst *et al.* 2012, 2014; Table 4). The observed differences between- and within-spreading mechanism configurations can be discussed according to the key underlying engineering changes and possible species-specific responses, and ultimately used to provide directions for ongoing research.

There were clear between-system drag differences which highlight the important contribution of the otter boards to the relevant cumulative total drag. Specifically, despite their 25% longer headline lengths (and associated 33% greater twine area) and not withstanding slight differences in spread ratio (see below), the beam-trawls had significantly lower drags (up to 31%, corresponding to ~ 1.9 L less fuel per h) than the otter trawls. By considering the tension in the towing warp and the sweep wires (calculated from netting drag), the total hydrodynamic forces and the ground shear, it is possible to estimate the contribution of the otter boards towards total system drag at ~45% (Sterling 2000). Understanding the extent of such a contribution is important, since irrespective of between-system changes, simple alterations to the design (e.g. foil shape and aspect ratio) or configuration (e.g. AOA) of existing otter boards could improve trawl efficiency.

While more detailed investigations of otter-board performance in response to rigging arrangements/configurations are required, it is evident that simply removing the sweep wires significantly increased wing-end spread and with some (albeit non-significant) increase in drag (the predicted mean was 6 kg greater). This result can be attributed to a slight reduction in bridle angle caused by a narrower total gear span as the sweeps were removed. The lower bridle angle meant that less overall spreading force from the otter boards was required, with the surplus simply increasing SR.

Irrespective of the sweeps, both otter-trawl configurations also had greater SRs than the beam trawls (i.e. predicted mean differences of 0.02 and 0.06). Such differences warrant consideration, not only in terms of engineering performances but also relative catching efficiencies. For example, in a recent study Broadhurst *et al*. (2014) showed that compared to beam trawls rigged at a SR of 0.5, the same designs configured at between 0.6 and 0.8 caught significantly fewer *M. macleayi* and fish per trawled ha. One explanation for this result was that the corresponding steeper wing angles increased the probability of mesh encounters and escape for *M. macleayi* and were less efficient for herding fish (Broadhurst *et al.* 2014).

While the possibility for confounding effects of SR exist here, it was considered either unlikely or of minimal importance for two reasons. First, the maximum difference between SRs here was a lot lower than those tested by Broadhurst *et al*. (2014) (e.g. 9 vs 25−60%) and so the geometric consequences might also be minimal. Second, unlike the earlier study and independent of all other variables, positive correlations were observed between catches of both *M. macleayi* and *H. castelnaui* (the only teleost significantly impacted by any of the treatments) and SR. Assuming few confounding SR effects, the observed differences in catches can be attributed to the key treatment effects of interest: the spreading mechanisms and within-system changes.

For some variables, including the non-responsive shell debris and *C. mosaicus*, the direct consequences of the above within- and between-system engineering changes were evident in their absolute catches (per 40-min deployment). For example, removing the sweeps meant that shells disturbed by the otter boards were directed into the wings, instead of passing anteriorly, while the beam-trawl configurations caught more *C. mosaicus*, simply because of the longer headline. However, such simple trends were not apparent for the other key species—results that probably reflect behavioural responses to stimuli and therefore need to be discussed in terms of standardised catches (to remove the confounding effects of different swept areas).

With respect to *M. macleayi* behaviour, it is well established that most individuals reside in or on the substratum during the day (Ruello 1973). Other studies have shown that the typical response of such benthic-orientated penaeids to external stimuli is to contract their abdomen, which in the case of a contact with a footrope, propels them upwards and into the trawl mouth (Watson 1989). After subsequent contractions (and random propulsions) within the trawl, individuals were observed to attempt to orientate back into the substratum, but inevitably were directed by the panels of netting into the codend (Watson 1989).

Like the footrope, otter boards might be expected to disturb *M. macleayi* and potentially direct some towards the approaching trawl (Broadhurst *et al.* 2012, 2014). In this study, we attempted to test this hypothesis by also standardising *M. macleayi* catches to total-system contact (which included the span of the otter-board baseplates on the substratum), although the otter trawls still retained significantly more *M. macleayi* than the beam trawls. However, such a result could indicate that otter boards are more than 100% efficient for their span. For example, owing to their weight, otter boards penetrate the substratum more deeply than the footrope, and are thus likely to disturb more buried organisms (Kaiser *et al.* 2002).

The potential behavioural response of *M. macleayi* to the otter boards might also explain why there was a significant reduction in catches and a bias towards smaller individuals in the absence of sweeps. Removing the sweep wires would reduce the opportunity for any *M. macleayi* disturbed by the otter boards to settle back into the substratum before being overtaken by the trawl. It is also possible that because the swimming ability of individuals might be proportional to their size (e.g.

Daniel & Meyhofer 1989), some of the larger *M. macleayi* disturbed by the otter boards might have escaped over the headline, explaining the observed size differences.

Although speculative in the absence of *in situ* observations, the observed size bias and significant reduction in *M. macleayi* catches by the beam trawl with the horizontal wire might be explained by similar behaviour as above. The length and likely motion of the plastic strips meant that they could have disturbed the substratum anterior to the trawl mouth and in doing so, may have stimulated some *M. macleayi* before they encountered the ground gear, facilitating their escape.

Like for *M. macleayi*, species-specific behavioural responses could explain the observed differences in catches of *H. castelnaui* between and within spreading mechanisms. For example, previous studies have identified positive relationships between sweep length and fish catches, although the effects can be quite species-specific; potentially reflecting a range of variables, including swimming performances, and perhaps responses to visual or tactile stimuli (Engås & Godø 1989; Wardle 1989; Andrew *et al.* 1991). The results here support this trend with *H. castelnaui* the only species (of the six assessed) that significantly responded to the horizontal or sweep wires.

The differential, consistent response of *H. castelnaui* to the between- and within-system changes might reflect their extensive schooling behaviour. Other schooling species (e.g. gadoids and a scombrid) have been observed to orientate equidistant between those components offering the greatest stimuli (e.g. the otter boards and sweep wires) with their subsequent retention in trawls influenced by their swimming capacity and endurance (Main & Sangster 1983). If the same stimuli affected *H. castelnaui*, then removing the sweep wires or adding a horizontal wire might be expected to negatively and positively affect the extent of reactions and therefore catches, depending on behavioural reactions in front of the trawl.

Trawling primarily relies on visual stimulus in the catching process, but fish reactions depend on a mixture of stimuli from the various trawl components (Main & Sangster 1983; Glass & Wardle 1989). For example, the colour and contrast of the gear will impact the visual senses while parts of the rigging (e.g. chains and shackles) will provide their own unique auditory signals, with tactile responses likely when visual stimuli are reduced or absent (Main & Sangster 1983; Glass & Wardle 1989). While we standardised the visual stimulus within treatments (e.g. the netting material and the spreading mechanisms within configurations were identical) the modifications would have disrupted consistency. Further research is required to more closely assess the stimuli evoking a response in *H. castelnaui* and also to elicit responses among other key species. Part of this work should include assessments of the utility of the above modifications at night (e.g. when many penaeid-trawl fisheries operate) because visual cues will be reduced (Andrew *et al.* 1991; Walsh 1996).

Irrespective of the actual mechanisms contributing to the differences in catches, this study has important implications for ongoing work to improve the environmental efficiency of trawls. Specifically, choosing an appropriate sweep length (at least for penaeid trawls fished during the day) could represent a simple mechanism for improving species selectivity. Similarly, like for the beam trawl, it might be possible to extend a horizontal wire between otter boards. As part of this work, the hypotheses that any wires (either horizontal or sweep) provide auditory signals as they move through the water should be investigated.

With rising costs (e.g. fuel) and high unaccounted fishing mortality, applying appropriate modifications to penaeid trawls to improve fuel efficiencies and size and species selectivity has never been more pertinent. The results presented here illustrate the utility of within-system modifications to the anterior sections of penaeid trawls that are simple and require limited capital investment, but ultimately should contribute towards resolving the components of the above issues. Such characteristics support ongoing research.

Acknowledgments

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Table 1 Scientific and common names and numbers (except blue blubber jellyfish—weights in kg only) of organisms caught during the experiment.

Family	Scientific name	Common name	Total
Cnidarians			
Catostylidae	*Catostylus mosaicus*	Blue blubber jellyfish	78
Crustaceans			
Palaemonidae	*Macrobrachium novaehollandiae*	Freshwater prawn	37
Penaeidae	*Metapenaeus macleayi*	School prawns[1]	223,722
	Metapenaeus bennettae	Green tail prawn[1]	267
	Penaeus monodon	Tiger prawn[1]	39
	Peneaus plebejus	Eastern king prawn[1]	1,102
Portunidae	*Portunus armatus*	Blue swimmer crab[1]	19
	Scylla serrata	Giant mud crab[1]	2
Elasmobranch			
Dasyatididae	*Dasyatis* sp	Stingray	44
Molluscs			
Loliginidae	*Uroteuthis* sp	Squid	253
Teleosts			
Ambassidae	*Ambassis jacksoniensis*	Port Jackson glassfish	128
	Ambassis marianus	Ramsey's perchlet	859
Antennariidae	*Antennarius striatus*	Striate anglerfish	1
Apogonidae	*Siphamia roseigaster*	Pink-breasted siphonfish	124
Ariidae	*Arius graeffei*	Forktail catfish[1]	74
Carangidae	*Caranx sexfasciatus*	Bigeye trevally[1]	6
Clupeidae	*Herklotsichthys castelnaui*	Southern herring[1]	4,460
	Hyperlophus vittatus	Whitebait[1]	46

Table 1 continued.

Eleotridae	*Gobiomorphus australis*	Striped gudgeon	4
Engraulidae	*Engraulis australis*	Australian anchovy	470
Gerreidae	*Gerres subfasciatus*	Silver biddy[1]	660
Gobiidae	*Arenigobius bifrenatus*	Bridled goby	10
Hemiramphidae	*Arrhamphus sclerolepis*	Snubnose garfish[1]	1
	Hyporhamphus regularis	River garfish[1]	12
Monacanthidae	*Aluterus monoceros*	Unicorn leatherjacket	1
Monodactylidae	*Monodactylus argenteus*	Diamond fish	19
Mugilidae	*Liza argentea*	Flat-tail mullet[1]	26
	Mugil cephalus	Bully mullet[1]	197
Muraenesocidae	*Muraenesox bagio*	Common pike eel	1
Paralichthyidae	*Pseudorhombus arsius*	Largetooth flounder[1]	12
Platycephalidae	*Platycephalus fuscus*	Dusky flathead[1]	5
Plotosidae	*Euristhmus lepturus*	Long-tailed catfish[1]	86
Pomatomidae	*Pomatomus saltatrix*	Tailor[1]	971
Priacanthidae	*Priacanthus macracanthus*	Red bigeye	2
Sciaenidae	*Argyrosomus japonicas*	Mulloway[1]	2
Sillaginidae	*Sillago ciliata*	Sand whiting[1]	7
Soleidae	*Synclidopus macleayanus*	Narrow banded sole	13
Sparidae	*Acanthopagrus australis*	Yellowfin bream[1]	1,184
	Rhabdosargus sarba	Tarwhine[1]	31
Terapontidae	*Pelates quadrilineatus*	Trumpeter[1]	29
Tetraodontidae	*Tetractenos glaber*	Toadfish	147
Tetrarogidae	*Notesthes robusta*	Bullrout	8

[1]economically important

Table 2 Summaries of likelihood ratio test (LRT) statistics from linear mixed models assessing the importance of the fixed effect of spreading-mechanism configuration (otter trawls with and without sweep wires, and beam trawls with and without a horizontal wire) in explaining variability among engineering and biological variables. Numbers and weights were analysed per 40-min deployment and standardised to per ha trawled calculated using the footrope contact (average wing-end spread × distance trawled) and, additionally for *Metapenaeus macleayi*, the total-system contact ((i.e. wing-end spread + span of otter-board contact) × the distance trawled) and then log-transformed.

Variables	LRT
Engineering variables	
Wing-end spread	38.01***
Drag	20.78***
Biological variables	
Wt of *M. macleayi* 40 min^{-1}	20.24***
Wt of *M. macleayi* ha^{-1} of footrope contact	23.95***
Wt of *M. macleayi* ha^{-1} of total-system contact	20.76***
No. of *M. macleayi* 40 min^{-1}	21.14***
No. of *M. macleayi* ha^{-1} of footrope contact	24.49***
No. of *M. macleayi* ha^{-1} of total-system contact	24.11***
Mean CL of *M. macleayi*	8.36*
Wt of *Catostylus mosaicus* 40 min^{-1}	10.67*
Wt of *Catostylus mosaicus* $ha^{-1}$of footrope contact	5.92
Wt of empty shells 40 min^{-1}	88.29***
Wt of empty shells ha^{-1} of footrope contact	89.36***
Wt of fish bycatch 40 min^{-1}	16.79***
Wt of fish bycatch ha^{-1} of footrope contact	21.14***
No. of fish bycatch 40 min^{-1}	13.13**
No. of fish bycatch ha^{-1} of footrope contact	17.32***

Table 2 continued

No. of *Herklotsichthys castelnaui* 40 min^{-1}	22.30***
No. of *Herklotsichthys castelnaui* ha^{-1} of footrope contact	24.72***
No. of *Acanthopagrus australis* 40 min^{-1}	3.86
No. of *Acanthopagrus australis* ha^{-1} of footrope contact	4.83
No. of *Pomatomus saltatrix* 40 min^{-1}	4.61
No. of *Pomatomus saltatrix* ha^{1} of footrope contact	3.19
No. of *Ambassis marianus* 40 min^{-1}	1.31
No. of *Ambassis marianus* ha^{-1} of footrope contact	1.68
No. of *Gerres subfasciatus* 40 min^{-1}	1.73
No. of *Gerres subfasciatus* $ha^{-1}$of footrope contact	3.07
No. of *Engraulis australis* 40 min^{-1}	2.16
No. of *Engraulis australis* ha^{-1} of footrope contact	1.29

*$p < 0.05$

**$p < 0.01$

***$p < 0.001$

Table 3 Summary of predicted mean ± SE wing-end spreads (m), spread ratios, drags (kgf), and other mean performance indicators for the four spreading-mechanism configurations. Litres of fuel per ha were calculated using both the footrope (FRC–average wing-end spread × distance trawled) and total-system contacts (TSC−average wing-end spread + otter board span on the bottom) × distance trawled). Mean predicted drags were derived with a centred value of SOG and with zero current. Dissimilar superscript letters indicate significant differences detected in false-discovery-rate pairwise comparisons ($p < 0.001$).

	Otter trawl with sweep wires	Otter trawl without sweep wires	Beam trawl without a horizontal wire	Beam trawl with a horizontal wire
Otter board angle of attack (°)	36	39	na	na
Wing-end spread (m)	4.96 (0.04)^{A}	5.25 (0.04)^{B}	6.00 (0.00)^{C}	6.00 (0.00)^{C}
Spread ratio	0.67 (0.01)	0.71 (0.01)	0.65 (0.00)	0.65 (0.00)
Drag (kgf)	142.59 (30.71)^{A}	148.26 (30.66)^{A}	102.18 (26.58)^{B}	103.56 (30.73)^{B}
Fuel rate (L h^{-1})	6.738	7.075	5.224	5.294
Fuel intensity				
L ha^{-1} (FRC)	2.808	2.808	1.804	1.810
L ha^{-1} (TSC)	2.235	2.235	1.804	1.810
L kg^{-1}	0.990	1.237	1.008	1.320

Table 4 Summary of the acceptance (A) or rejection (R) of the null hypothesis (of no difference in the relative performance) for key response variables among the various pair-wise comparisons of the four treatments of interest; (i) otter trawl with sweep wires (O with W), (ii) otter trawl without sweep wires (O without W), (iii) beam trawl with a horizontal wire (B with W), and (iv) beam trawl without a horizontal wire (B without W).

Ho = no

Pairwise comparison	Prawns	Bycatch	Drag
O with W vs O without W	A	R	A
O with W vs B without W	R	R	R
O with W vs B with W	R	R	R
O without W vs B without W	R	A	R
O without W vs B with W	R	A	R
B with W vs B without W	R	A	A

List of figures

Figure 1

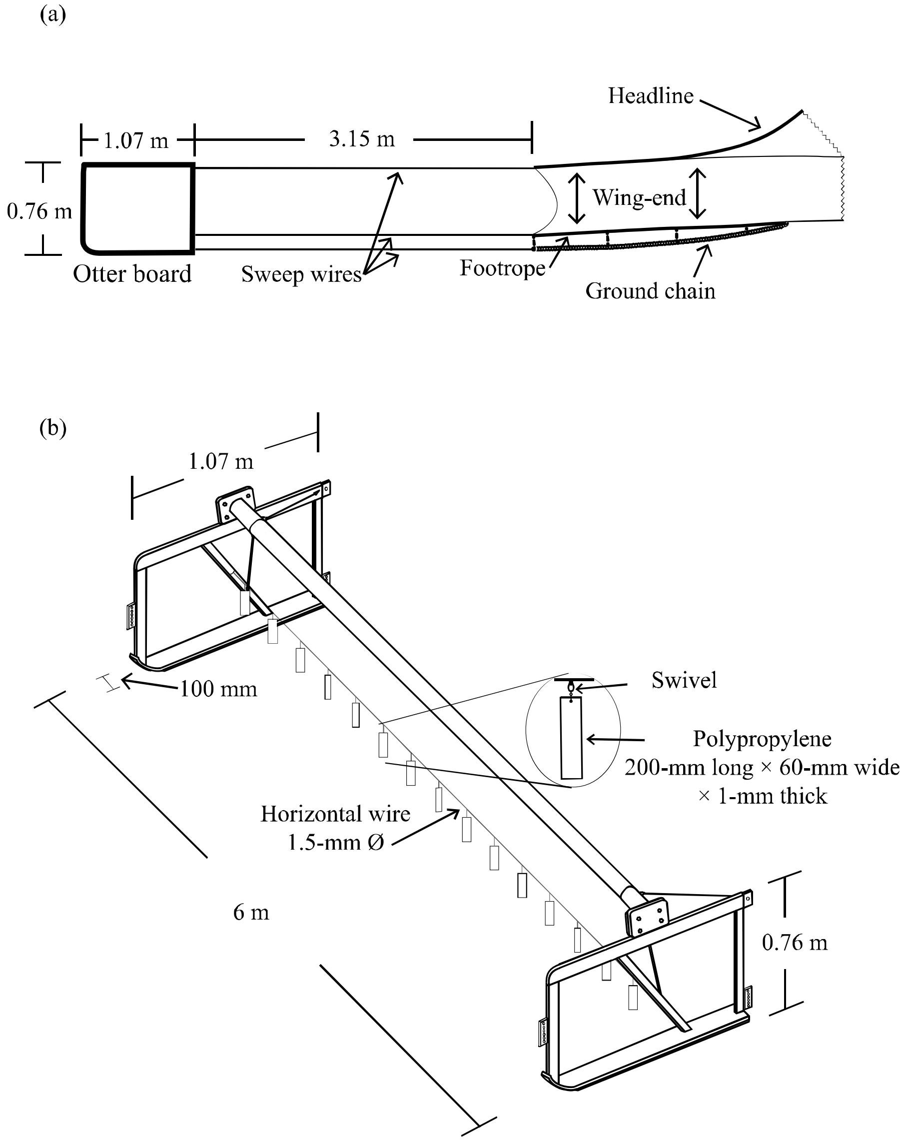

(a)
Headline
1.07 m
3.15 m
0.76 m
Wing-end
Otter board
Sweep wires
Footrope
Ground chain
(b)
1.07 m
100 mm
Swivel
Polypropylene
200-mm long × 60-mm wide
× 1-mm thick
Horizontal wire
1.5-mm Ø
6 m
0.76 m
(c) Otter trawl with
sweep wires
Bridles
Otter boards
Sweep wires
(d) Otter trawl without
sweep wires
Bridles
Otter boards
(e) Beam trawl
arrangement
sleds

Figure 2

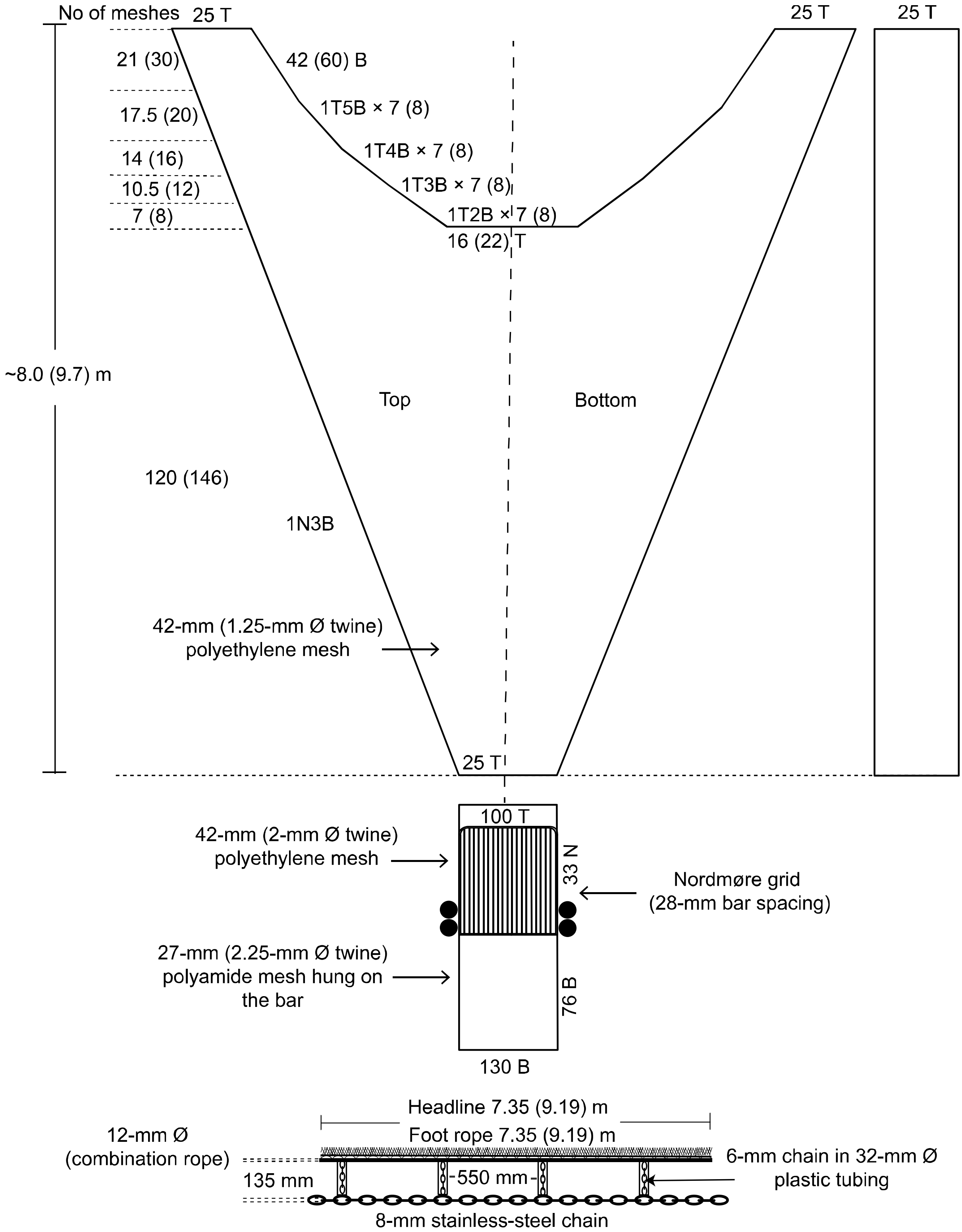

No of meshes
25 T
25 T
25 T
21 (30)
42 (60) B
17.5 (20)
1T5B × 7 (8)
14 (16)
1T4B × 7 (8)
10.5 (12)
1T3B × 7 (8)
7 (8)
1T2B × 7 (8)
16 (22) T
~8.0 (9.7) m
Top
Bottom
120 (146)
1N3B
42-mm (1.25-mm Ø twine) polyethylene mesh
25 T
100 T
42-mm (2-mm Ø twine) polyethylene mesh
33 N
Nordmøre grid (28-mm bar spacing)
27-mm (2.25-mm Ø twine) polyamide mesh hung on the bar
76 B
130 B
Headline 7.35 (9.19) m
Foot rope 7.35 (9.19) m
12-mm Ø (combination rope)
6-mm chain in 32-mm Ø plastic tubing
135 mm
550 mm
8-mm stainless-steel chain

Figure 3

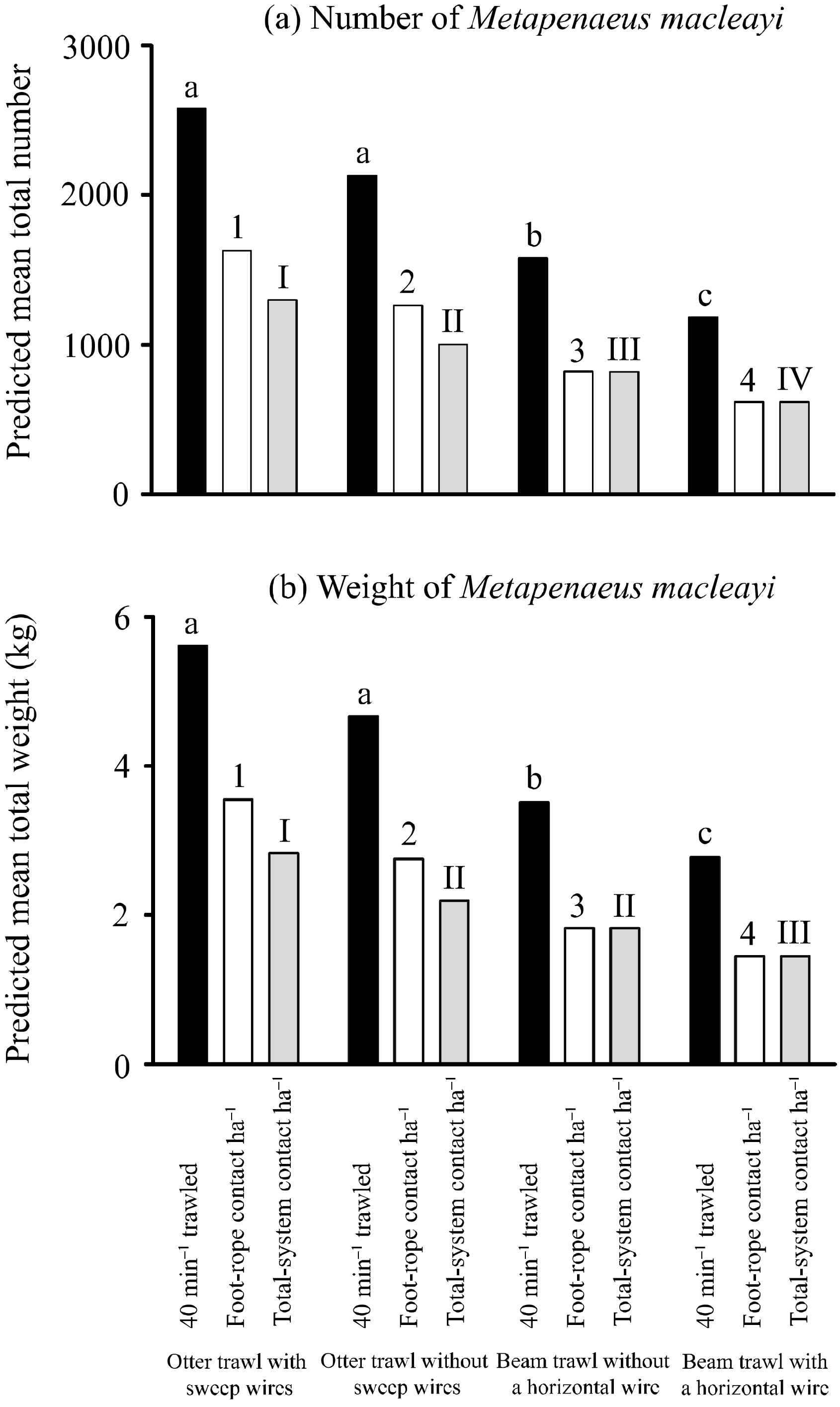

(a) Number of *Metapenaeus macleayi*
Predicted mean total number
0
1000
2000
3000
a
1
I
a
2
II
b
3
III
c
4
IV
(b) Weight of *Metapenaeus macleayi*
Predicted mean total weight (kg)
0
2
4
6
a
1
I
a
2
II
b
3
II
c
4
III
40 min^{-1} trawled
Foot-rope contact ha^{-1}
Total-system contact ha^{-1}
Otter trawl with sweep wires
Otter trawl without sweep wires
Beam trawl without a horizontal wire
Beam trawl with a horizontal wire

Figure 4.

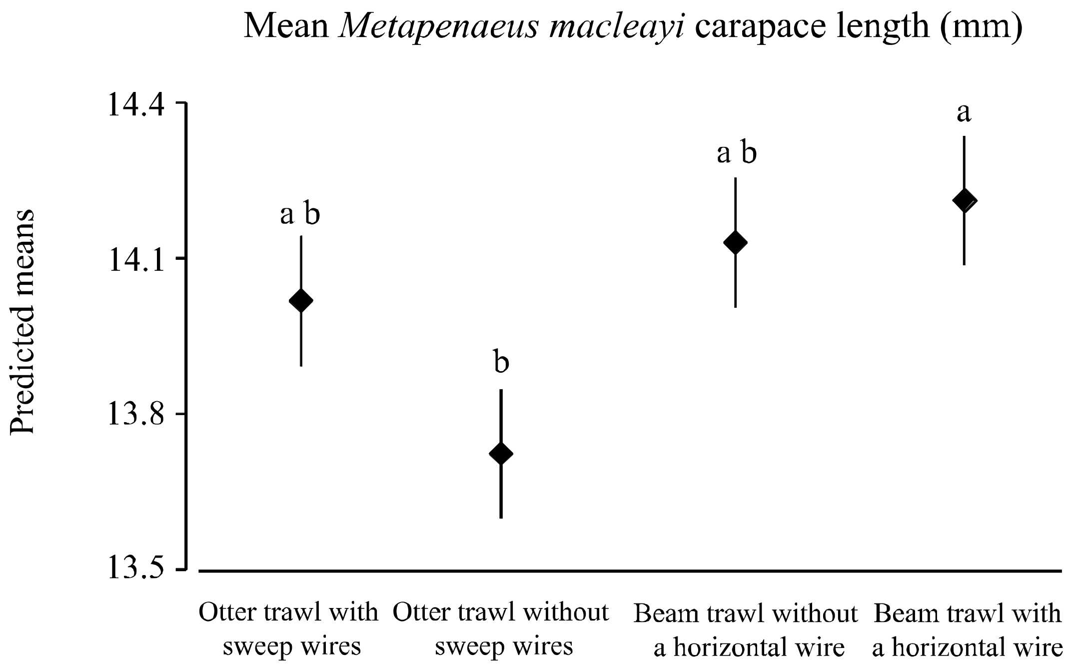
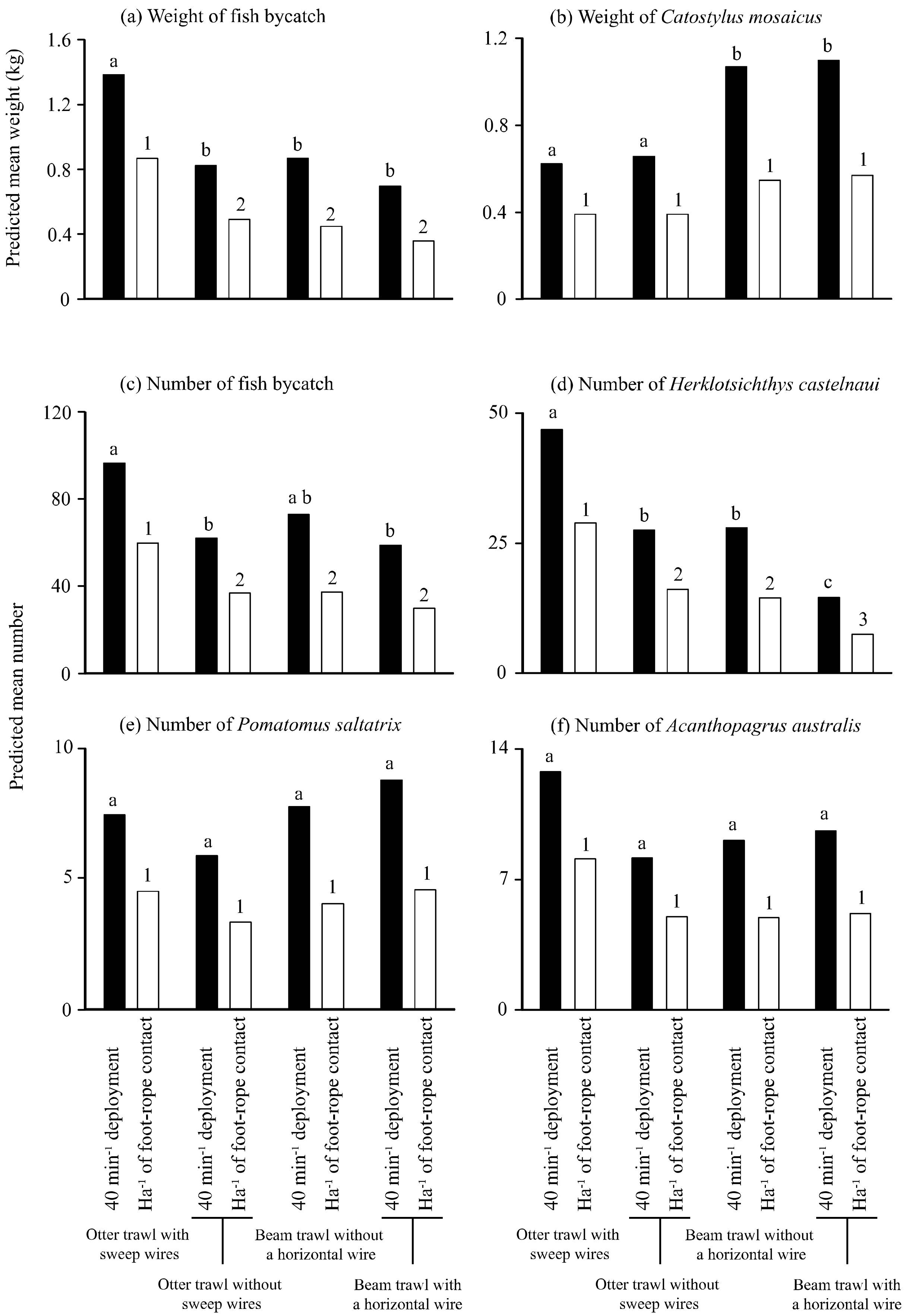

Mean *Metapenaeus macleayi* carapace length (mm)
Predicted means
14.4
14.1
13.8
13.5
a b
b
a b
a
Otter trawl with sweep wires
Otter trawl without sweep wires
Beam trawl without a horizontal wire
Beam trawl with a horizontal wire

Figure 5



(a) Weight of fish bycatch
(b) Weight of *Catostylus mosaicus*
(c) Number of fish bycatch
(d) Number of *Herklotsichthys castelnaui*
(e) Number of *Pomatomus saltatrix*
(f) Number of *Acanthopagrus australis*
Predicted mean weight (kg)
Predicted mean number
40 min⁻¹ deployment
Ha⁻¹ of foot-rope contact
Otter trawl with sweep wires
Otter trawl without sweep wires
Beam trawl without a horizontal wire
Beam trawl with a horizontal wire

Appendix 3. McHugh, M. J., Broadhurst, M. K., Sterling, D. J. and Millar, R. B. (2015) A 'simple anterior fish excluder' (SAFE) for mitigating penaeid-trawl bycatch. *PloS one* **10**(4), e0123124.

A 'simple anterior fish excluder' (SAFE) for mitigating penaeid-trawl bycatch

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Abstract

Various plastic strips and sheets (termed 'simple anterior fish excluders'−SAFEs) were positioned across the openings of penaeid trawls in attempts at reducing the unwanted bycatches of small teleosts. Initially, three SAFEs (a single wire without, and with small and large plastic panels) were compared against a control (no SAFE) on paired beam trawls. All SAFEs maintained targeted *Metapenaeus macleayi* catches, while the largest plastic SAFE significantly reduced total bycatch by 51% and the numbers of *Pomatomus saltatrix, Mugil cephalus* and *Herklotsichthys castelnaui* by up to 58%. A redesigned SAFE ('continuous plastic') was subsequently tested (against a control) on paired otter trawls, significantly reducing total bycatch by 28% and *P. saltatrix* and *H. castelnaui* by up to 42%. The continuous-plastic SAFE also significantly reduced *M. macleayi* catches by ~7%, but this was explained by ~5% less wing-end spread, and could be simply negated through otter-board refinement. Further work is required to refine the tested SAFEs, and to quantify species-specific escape mechanisms. Nevertheless, the SAFE concept might represent an effective approach for improving penaeid-trawl selectivity.

Keywords: SAFE, bycatch reduction, fish excluder, otter trawling, penaeids

Introduction

The capture and mortality of unwanted organisms (termed 'bycatch') by mobile demersal fishing gears is a global issue affecting many fisheries [1]. This is especially the case for penaeid trawling, which despite contributing only ~1.5% towards the total global marine wild harvest (estimated at a plateau of ~80 m t since 1985 [2]), accounts for >25% of all discarded bycatch (~7.3 m t per annum [1]); typically comprising small teleosts (<20 cm total length−TL), crustaceans and cephalopods [1, 3]. Historically, the mortality of such discards has raised wide-spread concerns, and primarily because of the potential for deleterious impacts on subsequent stocks [4, 5].

Considerable research has been done to mitigate penaeid-trawl bycatch and associated mortalities [6, 7]. Beyond temporal and spatial closures [7] the greatest efforts have focussed on retrospectively fitting 'bycatch reduction devices' (BRDs) to existing trawls. Broadly, such BRDs can be separated into two categories according to their principle separating function: those that rely on species-specific differences in size (termed 'mechanical-type BRDs'; e.g. the 'Nordmøre-grid'); or behaviour ('behavioural-type BRDs'; e.g. strategic 'square-mesh panels') to either actively or passively separate catches [6].

Notwithstanding their different classifications, the majority of BRDs are located in the posterior trawl (i.e. codend) and compared to conventional configurations can maintain penaeid catches within a ~10% loss, while reducing unwanted bycatches by ~30−70% [6]. Such results are positive, although there remains very little information on the mortality of organisms escaping BRDs (and therefore their ultimate benefit); primarily because accurate assessments are difficult, if not impossible, for many fisheries [8, 9]. However, because BRDs that facilitate the rapid escape of organisms with minimal physical contact (e.g. behavioural-type designs) should evoke low mortalities, an even more appropriate concept might be to anteriorly locate designs, and so promote complete trawl avoidance.

While the widespread use of such anterior BRDs is relatively uncommon, there have been successful attempts at demonstrating their utility [10]. For example, Seidel and Watson [10] designed a ‘fish barrier’, comprising mesh webbing across the trawl mouth that precluded the entry of large organisms, and used electrical stimulation to force penaeids up through an open benthic panel, and into the trawl. However, while this configuration had great potential, subsequently cheaper and more easily adaptable (to existing trawl codends) BRDs might have contributed towards its lack of commercial uptake. Also, some mesh-barrier designs (e.g. seal mitigation devices; [11]), placed at the trawl mouth can clog (e.g. with seaweed), which could either prevent penaeids entering or, alternatively, reduce wing-end spread and the area trawled [12].

The latter issue raises an important consideration. It is well established that complex BRDs are much less likely to be adopted and/or used correctly than those that are inexpensive and/or simple to maintain and operate [6]. Consequently, in terms of reducing unaccounted fishing mortality, the wide-scale use of simple and even marginally effective BRDs ultimately will have greater benefits than the limited use of far more effective designs. Given the above, an alternative to completely physically obstructing the trawl mouth may be to insert a behavioural-type BRD, which although being the less effective category of BRDs [6] should be smaller and less likely to affect trawl performance. While the concept of anterior behavioural-type BRDs is not new (e.g. [12]–[14]), the difficulty remains in focusing on the stimuli (e.g. visual or auditory) that will elicit the greatest response among non-target individuals without impacting on target species [15].

Irrespective of the BRD location (anterior or posterior) or type (behavioural or mechanical), during development there always should be an emphasis on hypotheses testing within a strong empirical experimental design [16]. To maximise penaeid catches while minimizing bycatch, any modifications should be clearly identified through systematic testing within the full range of possibilities [17, 18]. Methodically assessing modifications will facilitate further testing, acceptance or reassessment if the desired result is not achieved [17].

During a recent study in an Australian penaeid-trawl fishery, we tested an anteriorly located BRD that met some of the technical criteria discussed above [14]. Termed the 'simple anterior fish excluder' (SAFE), the design comprised a wire between beam-trawl sleds, from which 200- × 60- × 1-mm plastic strips were hung on universal swivels (allowing spinning). Compared to the control, the trawl with the SAFE reduced the catches of one species, southern herring, *Herklotsichthys castelnaui* by 48%, with minimal effect on catches of the targeted school prawns, *Metapenaeus macleayi*.

Here, we expand on the SAFE concept by first assessing the limits of practicality and effectiveness (including the original SAFE tested by McHugh et al. [14]) within a beam-trawl configuration before using this information to develop a prototype for testing on a more dynamic (i.e. non-rigid spreading mechanism) otter trawl. Specifically, our aims were to (i) test the hypothesis of no differences in the effectiveness of the SAFE area (i.e. 1, 3 and 11% of the two-dimensional opening) on the beam trawl and then, using this information, (ii) design and test an appropriate SAFE for use in otter trawling. The work was done in Australia, but the results have broader implications among other national and international crustacean-trawl fisheries.

Material and methods

Ethics statement

The research was done in Lake Wooloweyah (29°26′ S 153°22′ E) New South Wales (NSW) Australia and in accord with the Department of Primary Industries scientific collection permit (No. P01/0059(A)-2.0). No specific permissions were required for access to Lake Wooloweyah. This study did not involve endangered or protected species, and all fish were returned to the water as soon as practicable, following each trawl deployment. Animal ethics approval for the research was granted by the NSW DPI Animal Care and Ethics Committee (Ref. 08/06). This study complied with all relevant regulations pertaining to the conservation of the surrounding environment and nearby wildlife, as detailed in the scientific collection permit.

Location and vessel

Two experiments were completed in the Lake (sand and mud substrata ~1–2 m depth) during the Austral summer, 2013 on-board a 10-m double-rigged penaeid trawler (104 kw). The trawler had a global positioning system (Lowrance, HDS5) and two independent sum logs (model: Bronze + Log) to record speed over the ground (SOG) and through the water (STW; both in m s^{-1}). Load cells (Amalgamated Instrument Company; model no. PA6139) were configured so that they could be attached to bridles (always deployed to 12 m from paired winches) to measure the combined tension (kgf). The wing-end spreads of relevant otter trawls were obtained using Notus paired wireless sensors (see below). Data from the Notus sensors were received through an omnidirectional hydrophone and logged onto a laptop. All electronic data were recorded every 60 s.

Experiment 1: testing three different SAFEs on a beam trawl

For the first experiment, the trawler was rigged with identical, paired 6-m beam-and-sled (1.07 × 0.76 × 0.1 m; 108 kg) assemblies. These spreading mechanisms were anteriorly attached to the towing wires via a 7.3 m bridle (Figure 1a) and posteriorly to trawl bodies with 9.19 m headlines (and footropes) and constructed from nominal 41-mm mesh (stretched mesh opening–SMO) and 1.25-mm diameter−Ø twisted polyethylene (PE) twine (for a trawl plan, see [14]). Both trawl bodies had identical conventional Nordmøre-grids (28-mm bar spacing) and square-mesh codends (120 × 75 bars) made from nominal 27 mm SMO polyamide mesh (1.25-mm Ø twine) hung on the bar (Figure 1b).

Figure 1. Schematic representation of the (a) beam trawl showing towing bridle and attachment locations of the (I) small-plastic (polypropylene–PP) (60 × 200 × 1 mm), (II) large-plastic (PP) (200 × 200 × 1 mm) and (III) the single-wire (1.50-mm Ø stainless steel) simple anterior fish excluders (SAFEs) tested in experiment 1 and (b) otter trawl with the polyvinyl chloride (PVC) continuous-plastic SAFE tested in experiment 2. The extension (with Nordmøre-grid) and codend (c), used in both experiments, are highlighted. PA, polyamide; PE, polyethylene.

Three SAFE treatments were constructed; all stretched between the sleds at 0.3 above the baseplates (Figure 1a). The first treatment comprised a single 6-m long, 1.50-mm Ø stainless-steel wire (termed ‘single wire’) while the second and third had the same wires, but also included 12 evenly distributed flat strips (all 0.2 m long) of 1-mm thick green polypropylene (PP) that were either 0.06- (termed ‘small plastic’ and the same as those tested by McHugh et al. [14]) or 0.2-m (‘large plastic’) wide (Figure 1a). The PP strips were secured to the main line by a snap-lock (ball bearing) swivel that was attached midway along their leading edges (Figure 1a). Prior to the experiment, the small- and large-plastic strips were secured at several (e.g. centre, edge and middle) attachment points to a pole, which was pulled through the water (at ~1.50 m s^{-1}) alongside a wharf and filmed with a Hero 3^{+} GoPro. The plastic strips attached at the centre of their leading edges were observed to spin erratically.

On each fishing day, the paired beams were configured as either the control (i.e. no wire), or with one of the three SAFE treatments and deployed for 40 min. The control and SAFE treatments were then alternated, so that we completed one paired comparison of all four configurations on each day (i.e. six daily deployments). The two trawls were also swapped from side-to-side after the first three deployments, while the load cells were daily rotated from side-to-side. Over seven days, we completed 21 replicate deployments of each SAFE and the control.

Experiment 2: testing a SAFE on an otter trawl

During the second experiment, the beam trawls were replaced with otter trawls, and the towing wires attached directly to paired cambered otter boards (1.07 × 0.76 m each and a total weight of 108 kg; Figure 1b). Sweep wires (2.89-m) were secured posterior to the otter boards and to 7.35-m headline length trawls that were constructed from the same materials and designs as those in experiment 1 and configured with the exact same Nordmøre-grids and codends (Figure 1b; for a trawl plan see McHugh et al. [14]).

A single SAFE treatment was constructed for use with the otter trawls. Termed the ‘continuous-plastic’, this design comprised a hemmed sheet of flexible white polyvinyl chloride (PVC) measuring 0.2 m wide (same as the green PP strips) × 6.4 m long, through which a 7.25-m (1.50-mm Ø) stainless-steel wire was threaded and terminated in snap clips (Figure 1b). The length of the wire was calculated based on an average wing-end spread during previous testing of the two trawls, and this was extrapolated to derive the otter-board spread [14]. The continuous-plastic SAFE was attached between the otter-board towing points at 0.40 m above the baseplates, so that it extended across the front of the trawl (Figure 1b).

At the start of each fishing day, the Notus paired sensors were attached to the wing ends of the trawls on each side of the vessel. The continuous-plastic SAFE was alternately and randomly clipped in front of one trawl, with both then deployed for 40-min up to six times each day. After three deployments, the trawls were swapped from side-to-side, while the load cells and paired Notus sensors were similarity rotated each day. Over five days, we completed 26 replicate deployments of the control and continuous-plastic SAFE.

Data collected and statistical analyses

All trawl bodies and codends were checked for mesh uniformity by measuring 15 replicate SMOs using a local, purpose-built gauge. Other technical data collected during each deployment in each experiment included the: (i) warp tension (kgf) for each configuration; (ii) the total distance (m) trawled (sleds on and off the bottom – obtained from the GPS); and (iii) SOG and STW (m s^{-1}) (Table S1 and S2). Additionally, in experiment 2, data for wing-spread (m) were collected for each deployment (Table S2).

Biological data collected at the end of each deployment included the: total weights of the targeted *M. macleayi* and bycatch; numbers of each bycatch species; and total lengths (TL to the nearest 0.5 cm) of the most abundant teleosts. Random samples of ~500 g of *M. macleayi* were bagged and transferred to the laboratory, where they were measured (carapace length – CL in mm), weighed and counted. These latter data were used to estimate the total numbers and the mean CLs caught during each deployment.

The hypothesis of no differences in the mesh sizes within the four trawl bodies, and two extensions and codends was tested in a linear model (LM). Within each experiment, the remaining data were analysed in linear mixed models (LMMs), with some standardised prior to analyses. The numbers and weights of catches were analysed per 40-min deployment and also per ha trawled (calculated using the known beam- and observed otter-trawl wing-end distances and the distance trawled) and as log-transformed data so that predicted effects would be multiplicative. All other data, including the mean CL of *M. macleayi*, mean TL per deployment of sufficiently abundant teleosts (occurring in >95% of deployments), drag and area and distance trawled were analysed in their raw form.

All LMMs included ‘anterior-trawl configuration’ (i.e. SAFEs vs. controls) as a fixed effect, while ‘trawls’, ‘sides’, ‘days’ and deployments (within days) were included as random terms. For the LMM assessing drags, ‘load cell’ was included as an additional random term while additional fixed co-variates included ‘SOG’, ‘STW’ (with ‘sum-log’ as a random term) and ‘flow’ (calculated as the speed of the current in the direction of travel and defined as SOG–STW). The preferred models were chosen based on forward variable selection with a p-value of 0.05 required for an effect to enter the model. All models were fitted using either the lmer function from the lme4 package or ASReml in R 2.15.3 (The R Project for Statistical Computing; http://www.r-project.org/), with the significance of anterior-trawl configuration determined using a Wald *F*-value. In experiment 1, any significant Wald *F*-values for anterior-trawl configuration were subsequently explored using the Benjamini-Hochberg-Yekutieli procedure to control the false discovery rate (FDR) for multiple pair-wise comparisons [19].

Results

There were no significant differences in the SMO between trawl bodies (means ± SE of 41.25 ± 0.08 mm), extensions (41.40 ± 0.17 mm) or codends (27.35 ± 0.10 mm) (LM, $p > 0.05$). Pooled across experiments, the trawls caught 1753 and 154 kg of *M. macleayi* and total bycatch (Table 1). The total bycatch included 29 species, but in experiment 1, tailor, *Pomatomus saltatrix* (5.5–18.5 cm T), bully mullet, *Mugil cephalus* (5.5–15.5 cm TL), silver biddy, *Gerres subfasciatus* (5.0–13 cm TL), Ramsey's perchlet, *Ambassis marianus* (3.5–10.5 cm TL), yellowfin bream, *Acanthopagrus australi*s (4.0–23.5 cm TL), and southern herring, *H. castelnaui* (6.5–16.5 cm TL) comprised >85% of catches (Table 1). In experiment 2, *A. marianus* (5.0–13.5 cm TL), *P. saltatrix* (4.0–17 cm TL), *G. subfasciatus* (6.5–13.5 cm TL), *H. castelnaui* (5.5–15 cm TL), *A. australi*s (5.0–25 cm TL), and tarwhine, *Rhabdosargus sarba* (5.5–11 cm TL) were most prevalent (>77%; Table 1). These seven species, along with *M. macleayi*, form the basis of the biological analyses.

Table 1. Scientific and common names and numbers (except blue blubber jellyfish, *Catostylus mosaicus*—weights in kg only) of organisms caught during experiments (Exp.) 1 and 2. −, not present in catches.

Family	*Scientific name*	*Common name*	Exp. 1	Exp. 2
Cnidarians				
Catostylidae	*Catostylus mosaicus*	Blue blubber jellyfish	108	40
Crustaceans				
Palaemonidae	*Macrobrachium novaehollandiae*	Freshwater prawn	2	–
Penaeidae	*Metapenaeus macleayi*	School prawn[1]	584,044	147,116
	Metapenaeus bennettae	Green tail prawn[1]	21	49
	Penaeus monodon	Tiger prawn[1]	7	3
Portunidae	*Portunus pelagicus*	Blue swimmer crab[1]	6	6
Elasmobranchs				
Dasyatididae	*Dasyatis* sp	Stingray	–	1
Molluscs				
Loliginidae	*Uroteuthis* sp	Squid[1]	368	201
Teleosts				
Ambassidae	*Ambassis jacksoniensis*	Port Jackson glassfish	324	57
	Ambassis marianus	Ramsey's perchlet	470	1,058
Ariidae	*Arius graeffei*	Forktail catfish[1]	1	22
Apogonidae	*Siphamia roseigaster*	Pink-breasted siphonfish	129	65
Carangidae	*Gnathanodon speciosus*	Golden trevally[1]	1	−
	Pseudocaranx dentex	Silver trevally[1]	−	1
	Trachurus novaezelandiae	Yellowtail scad[1]	1	2
Clupeidae	*Herklotsichthys castelnaui*	Southern herring	400	369
	Hyperlophus vittatus	Whitebait	−	5
Engraulidae	*Engraulis australis*	Australian anchovy	45	13
Gerreidae	*Gerres subfasciatus*	Silver biddy	507	447
Hemiramphidae	*Arrhamphus sclerolepis*	Snubnose garfish[1]	3	4
	Hyporhamphus regularis	River garfish[1]	16	–

Monodactylidae	*Monodactylus argenteus*	Diamond fish	2	6
Mugilidae	*Liza argentea*	Flat-tail mullet[1]	24	3
	Mugil cephalus	Bully mullet[1]	1,046	64
Muraenesocidae	*Muraenesox bagio*	Common pike eel	1	4
Paralichthyidae	*Pseudorhombus arsius*	Largetooth flounder	15	23
Platycephalidae	*Platycephalus fuscus*	Dusky flathead[1]	1	9
Plotosidae	*Euristhmus lepturus*	Longtail catfish	61	175
Pomatomidae	*Pomatomus saltatrix*	Tailor[1]	4,087	937
Scatophagidae	*Selenotoca multifasciata*	Old maid	–	1
Sciaenidae	*Argyrosomus japonicus*	Mulloway[1]	2	2
Sillaginidae	*Sillago ciliata*	Sand whiting[1]	–	2
Soleidae	*Synclidopus macleayanus*	Narrow banded sole	1	−
Sparidae	*Acanthopagrus australis*	Yellowfin bream[1]	420	328
	Rhabdosargus sarba	Tarwhine	65	202
Terapontidae	*Pelates quadrilineatus*	Trumpeter[1]	13	4
Tetraodontidae	*Tetractenos glaber*	Toadfish	8	271

[1]economically important

Experiment 1: testing three different SAFEs on a beam trawl

The four beam-trawl configurations were towed at similar SOGs and STWs (ranging from 1.23 to 1.28 m s^{-1}) covering predicted mean ± SE areas between 1.90 ± 0.02 and 1.95 ± 0.02 ha per 40-min deployment, which were not significantly different (LMM, $p > 0.05$; Table 2). None of the SAFEs significantly affected drag (predicted means ± SE between 205.3 ± 2.2 and 208.2 ± 2.2 kg, LMM, $p > 0.05$; Table 2). STW and SOG were both positively correlated with drag, but they were not statistically significant ($p > 0.05$).

Table 2. Summaries of Wald *F*-values from linear mixed models assessing the importance of the fixed effect of anterior-trawl configuration (SAFEs vs. controls) in explaining variability among engineering and biological variables. Numbers and weights were analysed per 40-min deployment and standardised to per ha trawled calculated using the footrope contact (wing-end spread × distance trawled) and then log-transformed. −, not relevant.

	Experiment 1	Experiment 2
	Wald *F*	Wald *F*
Engineering variables		
Wing-end spread	−	4.19*

Drag	0.62	0.004
Hectare trawled	2.17	22.46***
Biological variables		
Wt of *Metapenaeus macleayi* 40 min^{-1}	2.53	4.52*
Wt of *M. macleayi* ha^{-1}	2.56	0.19
No. of *M. macleayi* 40 min^{-1}	1.56	1.46
No. of *M. macleayi* ha^{-1}	1.58	0.19
Mean CL of *M. macleayi* 40 min^{-1}	1.55	5.41*
Wt of fish bycatch 40 min^{-1}	22.81***	12.16**
Wt of fish bycatch ha^{-1}	23.54***	7.08*
No. of fish bycatch 40 min^{-1}	19.18**	9.33**
No. of fish bycatch ha^{-1}	19.75***	5.53*
No. of *Pomatomus saltatrix* 40 min^{-1}	15.09***	11.93**
No. of *P. saltatrix* ha^{-1}	17.34***	10.86**
Mean TL of *P. saltatrix* 40 min^{-1}	1.34	–
No. of *Mugil cephalus* 40 min^{-1}	5.06**	–
No. of *M. cephalus* ha^{-1}	4.99**	–
No. of *Herklotsichthys castelnaui* 40 min^{-1}	3.94*	7.00*
No. of *H. castelnaui* ha^{-1}	3.98*	5.73*
No. of *Gerres subfasciatus* 40 min^{-1}	1.49	1.66
No. of *G. subfasciatus* ha^{-1}	1.24	2.39
No. of *Ambassis marianus* 40 min^{-1}	1.77	0.15
No. of *A. marianus* ha^{-1}	1.45	0.01
No. of *Acanthopagrus australis* 40 min^{-1}	1.00	0.11
No. of *A. australis* ha^{-1}	1.07	0.38
No. of *Rhabdosargus sarba* 40 min^{-1}	–	0.25
No. of *R. sarba* ha^{-1}	–	0.14

*$p < 0.05$
**$p < 0.01$
***$p < 0.001$

Because there were no significant differences in the areas trawled, the biological data provided the same interpretations irrespective of standardization (i.e. to per ha; Table 2). Consequently, for convenience (and beyond Table 2), only the catches per 40-min deployment in experiment 1 are discussed and presented.

The anterior-trawl configuration had no significant effects on the catches, nor mean CL of *M. macleayi* (13.86–14.26 mm; LMM, $p > 0.05$), but did significantly influence the number and weight of total fish bycatch, and the numbers of *M. cephalus*, *H. castelnaui* and *P. saltatrix* (LMM, $p < 0.01$; Table 2; Figure 2a−g), but not the mean size of the latter (LMM, $p > 0.05$; Table 2). The significant effects on bycatch broadly were positively correlated with SAFE surface area (Figure 2b, d and e−g). Specifically, compared to the control and the single-wire SAFE, both the small- and large-plastic SAFEs significantly and incrementally reduced the weights (by up to 27 and 51%) and numbers (by up to 26 and 47%) of total fish bycatch (FDR, $p < 0.05$; Table 2, Figure 2b and d). The beam trawl with the large-plastic SAFE also caught significantly fewer *P. saltatrix* and *M. cephalus* than all other configurations (by up to 43 and 58%) and *H. castelnaui* than the control (by 49%; FDR, $p < 0.05$; Table 2, Figure 2e–g). No other fish were significantly affected by the SAFEs, although the numbers of *G. subfasciatus* and *A. australi*s followed similar trends as above (LMM, $p > 0.05$; Table 2, Figure 2h and i).

Figure 2. Differences in predicted mean weights of (a) school prawns, *Metapenaeus macleayi*, and (b) total fish bycatch, and the predicted mean numbers of (c) school prawns, (d) total fish bycatch, (e) tailor, *Pomatomus saltatrix*, (f) bully mullet, *Mugil cephalus*, (g) southern herring, *Herklotsichthys castelnaui*, (h) silver biddy, *Gerres subfasciatus*, (i) yellowfin bream, *Acanthopagrus australi*s and (j) Ramsey's perchlet, *Ambassis marianus* per 40-min deployment between the control and three SAFEs (single-wire, small-plastic and large-plastic) tested in experiment 1. Shaded histograms indicate significant wald *F*-values, while '>' and '=' indicate differences detected in false-discovery-rate pair-wise comparisons ($p < 0.05$).

Experiment 2: testing a SAFE on an otter trawl

The parsimonious LMM describing drag included SOG and anterior-trawl configuration as main effects, with the latter not significantly different between the control (259.5 ± 5.0 kg) and SAFE (259.7 ± 5.0 kg) trawls ($p > 0.05$; Table 2). Irrespective of anterior-trawl configuration, SOG was positively associated with drag (LMM, $p < 0.05$).

There was a significant difference in wing-end spreads between configurations, with the control (4.31 ± 0.21 m) spread 0.21 ± 0.05 m wider than the SAFE (LMM, $p < 0.05$; Table 2). Both configurations shared a common negative association with STW (LMM, $p < 0.01$). The control trawl fished a significantly greater area than the SAFE (1.43 ± 0.10 vs. 1.34 ± 0.10 ha) (LMM, $p < 0.001$; Table 2).

The slightly narrower trawl wing-end spread due to the continuous-plastic SAFE was reflected in a significant reduction (~7%) in the weight of *M. macleayi* per 40-min deployment (LMM, $p < 0.05$; Table 2, Figure 3a). However, when standardised to per ha, the number and weight of *M. macleayi* were not significantly different between trawls (LMM, $p > 0.05$; Table 2, Figure 3a and c), although the predicted mean CL was significantly smaller in the trawls with the SAFE (14.72 ± 0.20 mm) than the control (14.91 ± 0.20 mm) (LMM, $p < 0.05$; Table 2).

Figure 3. Differences in predicted mean weights of (a) school prawns, *Metapenaeus macleayi*, and (b) total fish bycatch, and the predicted mean numbers of (c) school prawns, (d) total fish bycatch, (e) tailor, *Pomatomus saltatrix*, (f) southern herring, *Herklotsichthys castelnaui*, (g) silver biddy, *Gerres subfasciatus*, (h) tarwhine, *Rhabdosargus sarba*, (i) yellowfin bream, *Acanthopagrus australis* and (j) Ramsey's perchlet, *Ambassis marianus* per 40-min deployment and standardised to per ha trawled using the footrope contact (average wing-end spread × distance trawled) between the control otter trawl and that containing the continuous-plastic SAFE tested in experiment 2. Shaded histograms indicate significant differences detected by Wald *F*-values ($p < 0.05$).

Compared to the control, the trawl with the continuous-plastic SAFE caught significantly less total bycatch by weight (by 28%) and number (24%) and fewer *P. saltatrix* and *H. castelnaui* per 40-min deployment and ha trawled (both by up to 42%) (LMM, $p < 0.05$; Table 2, Figure 3b, and d−f). Catches of the remaining key species were not significantly affected by the continuous-plastic SAFE (LMM, $p > 0.05$; Figure 3g–j).

Discussion

This study validates the concept of locating simple BRDs anterior to penaeid trawls for improving their species selectivity [13, 14]. Like in our earlier, preliminary study [14], the SAFEs tested here maintained target catches at acceptable limits and, for the otter trawl, the bycatch reductions rivalled those observed for other traditional posteriorly located BRDs [6]. The SAFEs' effectiveness can be discussed firstly according to the utility of the experimental approach, and then the related probable species-specific responses.

The limits/range of the original SAFE concept described by McHugh et al. [14] were somewhat defined in experiment 1 by incrementally testing larger modifications, involving a horizontal wire with and without small and large plastic attachments, across the beam trawl. Specifically, the sizes of the individual plastic strips—∽0.23 m long (PP strip and swivel)—were close to what we considered the maximum in terms of not contacting the top of the beam (0.76 m high), each other, nor the substrate during fishing, and potentially impacting on *M. macleayi* catches. However, notwithstanding the considerable bycatch reduction (up to 51%), the maintenance of *M. macleayi* catches at the same levels as the control, suggest that a slightly larger SAFE might have had some utility. Following this logic, we increased the area (from 11 to 23% of the trawl mouth) in the SAFE used on the otter trawl. Further, because the independent plastic strips comprising the SAFEs used on the beam trawl would have been easily entangled among the otter-trawl components (e.g. otter boards and sweep wires as they came together at the surface after each deployment), we chose a continuous-plastic strip.

While the continuous-plastic SAFE did not affect otter-trawl drag, it significantly decreased wing-end spread, the area trawled per deployment, and therefore the catches of *M. macleayi*. The narrower wing-end spread can probably be explained by the drag from the SAFE pulling the otter boards together which would have concomitantly reduced the drag of the trawl and ground-gear [20], providing the observed lack of change in total system resistance. It is also clear that a lower otter-board angle of attack (AOA) would have reduced the effective substrate contact and while speculative, this may have contributed to the negative impacts on *M. macleayi* catches—owing to fewer individuals (potentially those that were larger given the differences in mean size) being disturbed and directed into the path of the trawl [21]. Nevertheless, such catch effects were minimal and could be simply remedied by slightly increasing otter-board surface area.

The differences in wing-end spread due to the continuous-plastic SAFE had no negative effect on fish exclusion, with consistent, significant reductions both per 40 min and ha trawled. The SAFEs also maintained fish reductions between experiments, although the large-plastic SAFE used on the beam was considerably more effective (reducing total bycatch by up to 51% compared to the control) than the continuous-plastic SAFE used on the otter trawl. Although speculative, these results might be explained by the importance of visual cues in affecting fish reactions to towed gears, associated variation in trawl dynamics and potentially other environmental factors [22, 23].

Typically, the trawl capture process depends on fish being herded between the otter boards, sweep wires and trawl wings and then when fatigued, falling back into the codend [24]. This process is strongly affected by the elicited visual cues, whereby as water clarity decreases (e.g. low light or turbid conditions) so too does a fish's ability to detect gear-components and instigate an escape response [9, 15, 22, 23, 25]. Considering the above, in experiment 1 the horizontal wires on the beam remained taut and the plastic strips probably rotated freely and individually, potentially creating a strong visual stimulus for some fish. By comparison, in experiment 2, the continuous-plastic SAFE should have provided less movement and possibly reduced stimulus. Equally important, owing to the shallow concave shape of the SAFE, the angle at the otter boards would have increased, potentially herding some fish in towards the trawl path and negating some of the effectiveness.

Beyond the specific SAFE design, we also suggest that differences in fish density and water clarity may have been important factors contributing towards the observed inter-experimental variation in performances [15, 25]. For example, all three species affected by the SAFEs, but especially *P. saltatrix*, were caught in large numbers (comprising 73 and 32% of the total catches in each experiment). Potentially, intra-specific reactions within schools contributed towards their escape [25]. Future research to refine the SAFE would benefit from assessing the relationship between water clarity and effectiveness. However, because the extremely poor water clarity precludes using cameras, such work will require a manipulative-type experimental approach.

While turbidity was not measured, it was assumed to be comparable between experiments based on the trawling intensity occurring in the area at the time. Available meteorological data (www.bom.gov.au) suggest ambient light may have been lower during experiment 2 with three (of five) days having greater than 50% cloud cover compared to three (of seven) in experiment 1. The selectivity of *H. castelnaui* could have been influenced by the lower ambient light level, which limits the ability of some species to detect trawls [26].

Irrespective of the variability among performances, the observed bycatch reductions, combined with the simplicity and low cost of a SAFE (which should promote adoption as part of a legislated suite of existing, but more complex BRD designs in this fishery) support ongoing testing and refinement. As part of such work, it would be worthwhile to explore ways in which SAFEs could be engineered to concomitantly improve system engineering (and therefore reduce fuel usage). One potential option might be to use the SAFE to more accurately regulate otter-board AOA. It is well established that otter boards represent a large proportion (up to ∽30%) of trawl-system drag, which directly correlates to their AOA [27]. Most designs have a high AOA (>30^{o}) to increase stability during deployment, but can have greater operational efficiency at AOAs as low as 20^{o} [27]. Locating an appropriate length of SAFE at the leading edge of otter boards might achieve a lower AOA, and if so reduce some unnecessary system drag. Given the high global price of fuel, even a slight reduction in drag would help to promote industry adoption of the SAFE concept.

Another modification to improve the utility of the SAFE would be to configure a design that maintains a convex shape (away from the trawl mouth); potentially, helping to disperse fish away from the trawl [13]. While this may be difficult to achieve on an otter trawl (due to configuration constraints) such a design might be applicable on a beam trawl, and warrants further testing.

It is clear that trawl gear has evolved to exploit the behavioural and physiological responses of targeted species, but often with concomitant negative impacts on unwanted catches. Retrospectively fitted BRDs have been, and will continue to remain, an important applied strategy for mitigating bycatches, and ideally their associated unaccounted fishing mortality. Based on the results here, the SAFE concept might represent an effective approach for improving the selectivity of penaeid trawls.

Supporting information

S1 Table. Operational data, from sensors (load cells, and GPS), and catch statistics from experiment 1—testing three different SAFEs on a beam trawl.

S2 Table. Operational data, from sensors (load cells, GPS, and NOTUS), and catch statistics from experiment 2—testing a SAFE on an otter trawl.

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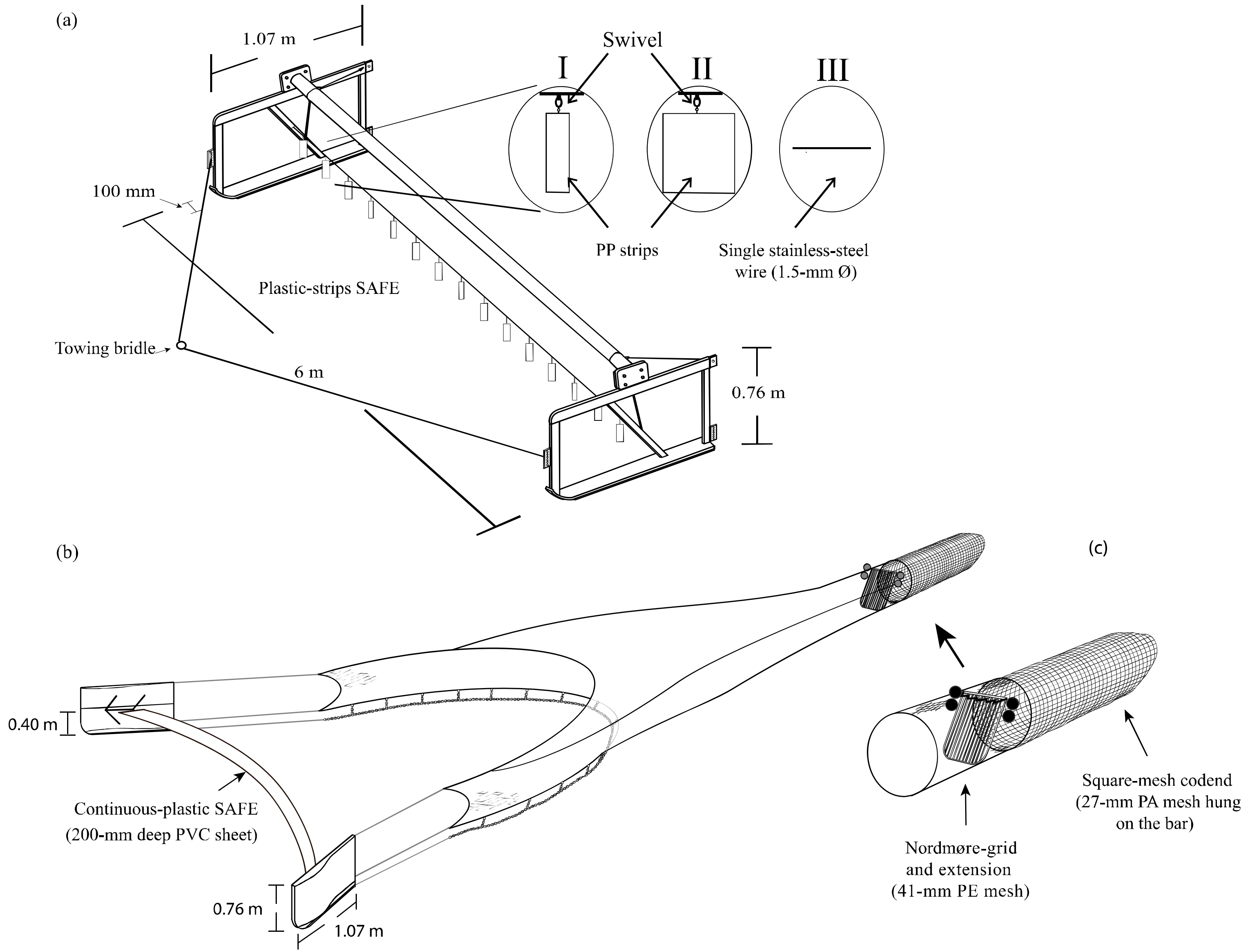
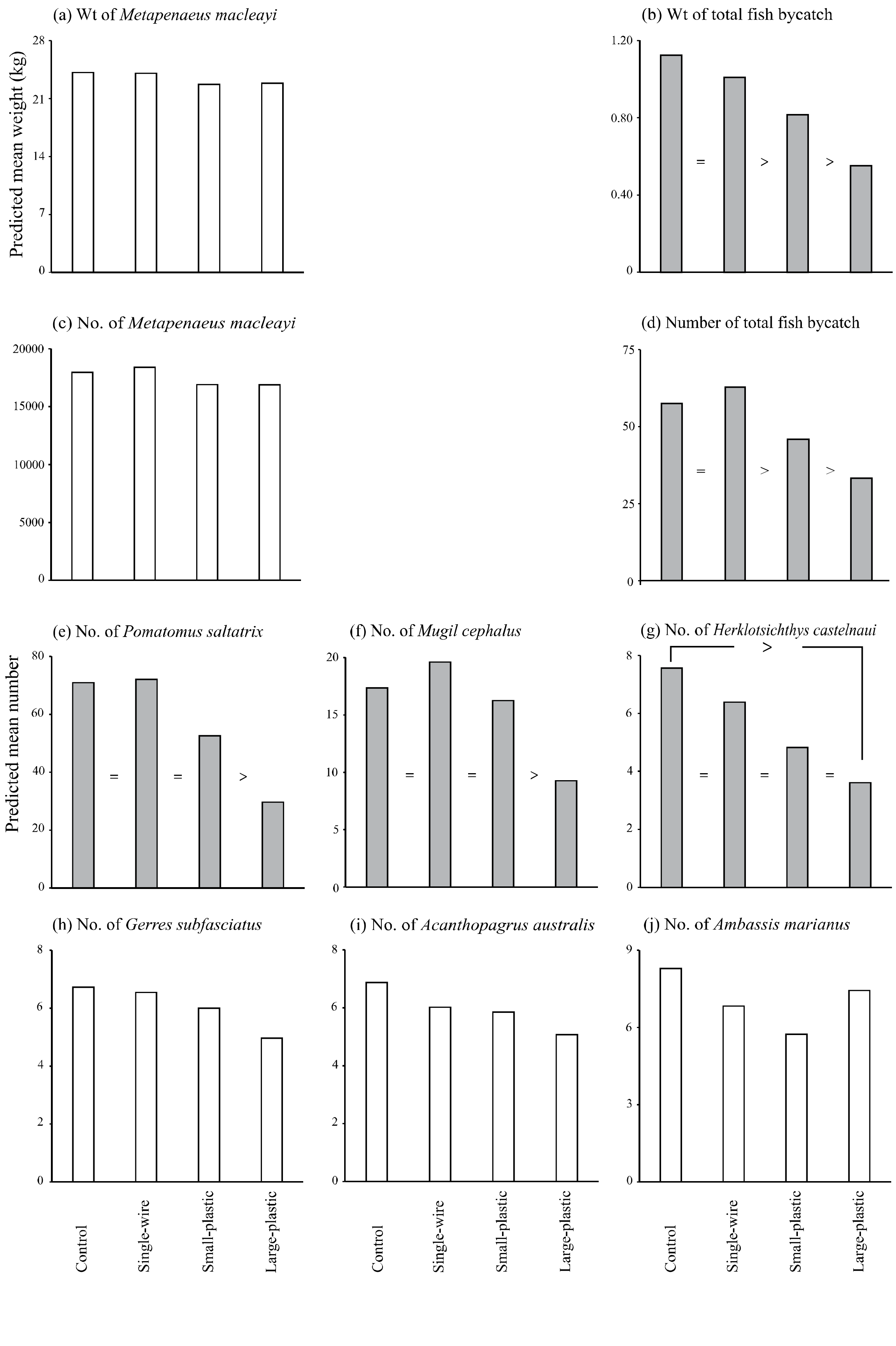

(a)
1.07 m
Swivel
I
II
III
100 mm
PP strips
Single stainless-steel
wire (1.5-mm Ø)
Plastic-strips SAFE
Towing bridle
6 m
0.76 m
(b)
(c)
0.40 m
Continuous-plastic SAFE
(200-mm deep PVC sheet)
0.76 m
1.07 m
Square-mesh codend
(27-mm PA mesh hung
on the bar)
Nordmøre-grid
and extension
(41-mm PE mesh)


(a) Wt of *Metapenaeus macleayi*
Predicted mean weight (kg)
28
21
14
7
0
(b) Wt of total fish bycatch
1.20
0.80
0.40
0
=
>
>
(c) No. of *Metapenaeus macleayi*
20000
15000
10000
5000
0
(d) Number of total fish bycatch
75
50
25
0
=
>
>
(e) No. of *Pomatomus saltatrix*
Predicted mean number
80
60
40
20
0
=
=
>
(f) No. of *Mugil cephalus*
20
15
10
5
0
=
=
>
(g) No. of *Herklotsichthys castelnaui*
8
6
4
2
0
>
=
=
=
(h) No. of *Gerres subfasciatus*
8
6
4
2
0
(i) No. of *Acanthopagrus australis*
8
6
4
2
0
(j) No. of *Ambassis marianus*
9
6
3
0
Control
Single-wire
Small-plastic
Large-plastic

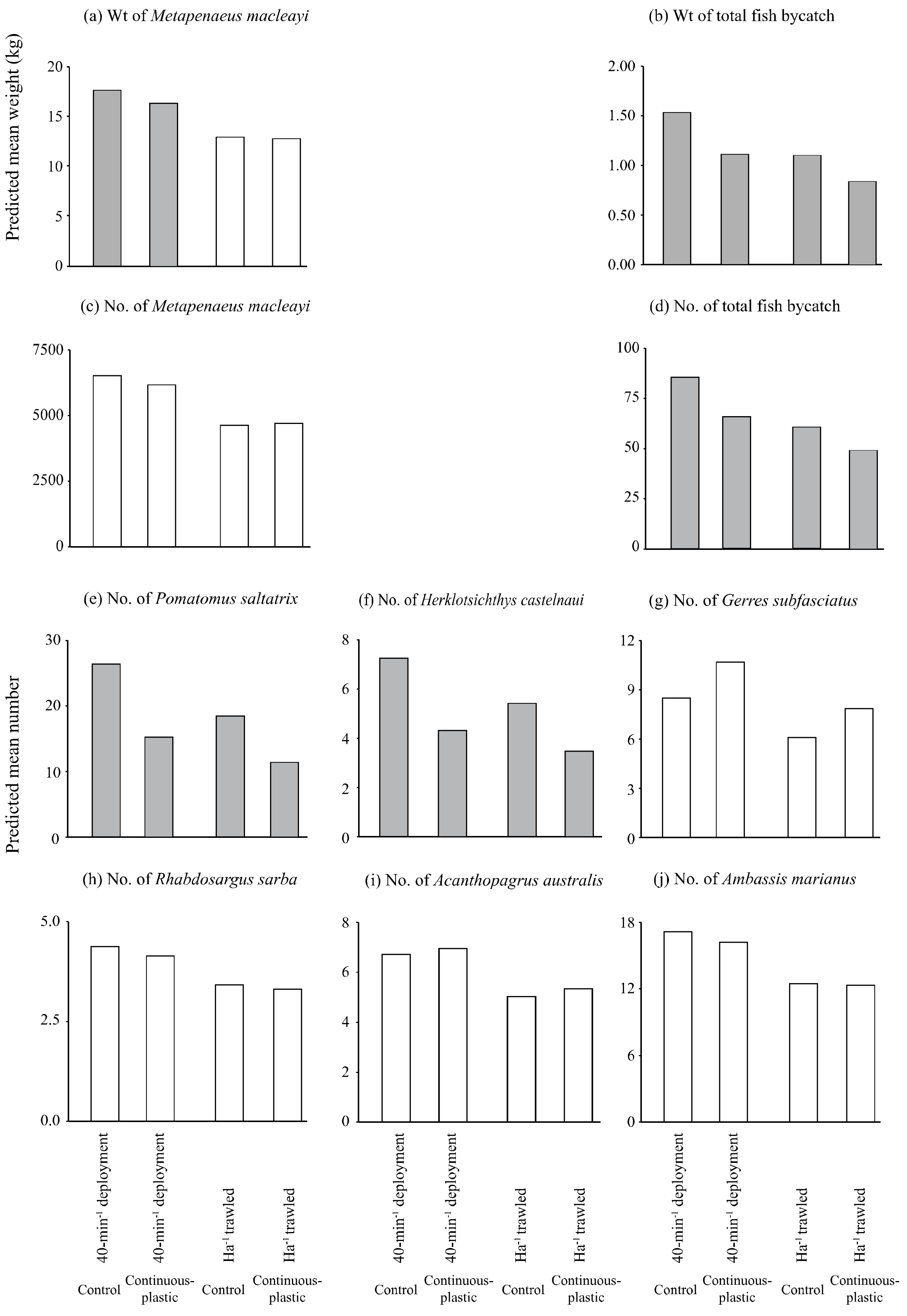

(a) Wt of *Metapenaeus macleayi*
(b) Wt of total fish bycatch
Predicted mean weight (kg)
20
15
10
5
0
2.00
1.50
1.00
0.50
0.00
(c) No. of *Metapenaeus macleayi*
(d) No. of total fish bycatch
7500
5000
2500
0
100
75
50
25
0
(e) No. of *Pomatomus saltatrix*
(f) No. of *Herklotsichthys castelnaui*
(g) No. of *Gerres subfasciatus*
Predicted mean number
30
20
10
0
8
6
4
2
0
12
9
6
3
0
(h) No. of *Rhabdosargus sarba*
(i) No. of *Acanthopagrus australis*
(j) No. of *Ambassis marianus*
5.0
2.5
0.0
8
6
4
2
0
18
12
6
0
40-min^{-1} deployment
Ha^{-1} trawled
Control
Continuous-plastic

Table S1. Operational data, from sensors (load cells, and GPS), and catch statistics from experiment 1—testing three different SAFEs on a beam trawl.

																Number											
Day no	**Haul**	**Treatment**	**Wing-end spread**	**Trawl load (kg)**	**Distance trawled (m)**	**Wing-end area trawled (Ha)**	**Average speed (m/sec)**	**Paired fuel used (L)**	**Total catch Weight (kg) 40-min**	**Total catch weight (kg) Ha^{-1}**	**Weight School prawns (kg) 40-min**	**Weight School prawns (kg) Ha^{-1}**	**No. School prawns 40-min**	**No. School prawns Ha^{-1}**	**CI School prawns**	**Yellowfin bream 40-min**	**Yellowfin bream Ha^{-1}**	**Bully mullet 40-min**	**Bully mullet Ha^{-1}**	**Ramsey's perchlet 40-min**	**Ramsey's perchlet Ha^{-1}**	**Southern herring 40-min**	**Southern herring Ha^{-1}**	**Silver biddy 40-min**	**Silver biddy Ha^{-1}**	**Tailor 40-min**	**Tailor Ha^{-1}**
1	2	Control	6	207.32	3.28	1.97	1.37	7.2	17.2	8.75	14.00	7.12	7.91	4.02	13.00	2	1.02	52	26.44	2	1.02	0	0.00	2	1.02	152	77.28
1	3	Control	6	216.46	3.32	1.99	1.38	7.4	13.2	6.64	9.20	4.63	4.51	2.27	14.50	8	4.02	1	0.50	9	4.52	1	0.50	2	1.01	48	24.13
1	6	Control	6	208.64	3.30	1.98	1.37	7.2	15.8	7.99	14.00	7.08	6.63	3.35	14.00	8	4.04	0	0.00	4	2.02	5	2.53	1	0.51	4	2.02
2	1	Control	6	206.67	3.32	1.99	1.38	6.7	29.48	14.82	26.50	13.32	12.71	6.39	14.50	8	4.02	12	6.03	10	5.03	32	16.09	6	3.02	116	58.32
2	4	Control	6	203.12	3.48	2.09	1.45	6.7	2.55	1.22	0.35	0.17	0.15	0.07	14.00	8	3.83	3	1.44	0	0.00	21	10.05	9	4.31	46	22.02
2	6	Control	6	229.96	3.20	1.92	1.33	7	2.42	1.26	0.40	0.21	0.19	0.10	14.80	2	1.04	1	0.52	5	2.60	11	5.72	5	2.60	43	22.37
3	1	Control	6	204.88	3.19	1.91	1.33	6.7	18.86	9.87	16.10	8.42	6.93	3.63	13.50	2	1.05	48	25.11	4	2.09	6	3.14	2	1.05	164	85.81
3	2	Control	6	213.09	3.20	1.92	1.33	6.9	23.98	12.47	21.90	11.39	10.10	5.26	15.00	4	2.08	49	25.49	1	0.52	0	0.00	0	0.00	66	34.33
3	5	Control	6	212.02	3.30	1.98	1.37	7.2	23.6	11.93	21.20	10.72	9.13	4.61	14.09	4	2.02	40	20.22	4	2.02	2	1.01	0	0.00	138	69.77
4	2	Control	6	209.92	3.28	1.97	1.37	7	10.5	5.34	8.40	4.27	3.42	1.74	15.00	1	0.51	7	3.56	5	2.54	0	0.00	0	0.00	46	23.39
4	4	Control	6	208.89	3.15	1.89	1.31	6.8	24.02	12.72	22.00	11.65	8.38	4.44	15.00	0	0.00	2	1.06	2	1.06	0	0.00	0	0.00	27	14.29
4	5	Control	6	208.88	3.32	1.99	1.38	7.1	21.74	10.93	19.80	9.95	8.77	4.41	13.92	0	0.00	15	7.54	1	0.50	1	0.50	2	1.01	64	32.18
5	2	Control	6	194.37	3.19	1.91	1.33	6.7	25.22	13.20	23.00	12.03	9.24	4.83	14.08	2	1.05	18	9.42	4	2.09	4	2.09	0	0.00	124	64.88
5	4	Control	6	212.28	3.22	1.93	1.34	7	40.04	20.71	39.00	20.17	17.95	9.29	13.58	2	1.03	6	3.10	4	2.07	3	1.55	0	0.00	57	29.48
5	5	Control	6	217.11	3.20	1.92	1.33	7	64.32	33.46	62.60	32.56	27.72	14.42	12.50	1	0.52	12	6.24	5	2.60	4	2.08	1	0.52	53	27.57
6	1	Control	6	205.75	3.15	1.89	1.31	6.9	3.2	1.69	2.32	1.23	0.85	0.45	15.50	0	0.00	16	8.47	2	1.06	16	8.47	2	1.06	32	16.94
6	3	Control	6	No Data	3.09	1.86	1.29	6.8	12.08	6.51	10.30	5.55	4.10	2.21	13.43	0	0.00	13	7.01	3	1.62	2	1.08	2	1.08	38	20.48
6	6	Control	6	212.35	3.26	1.96	1.36	7.1	10.6	5.42	8.20	4.19	3.58	1.83	14.00	2	1.02	16	8.18	8	4.09	10	5.11	0	0.00	48	24.54
7	1	Control	6	206.61	3.61	2.17	1.50	6.1	14.52	6.70	10.60	4.89	3.99	1.84	15.00	24	11.08	12	5.54	20	9.23	12	5.54	66	30.46	22	10.15
7	2	Control	6	206.59	2.80	1.68	1.17	6.3	9.92	5.91	8.50	5.07	3.34	1.99	14.80	5	2.98	3	1.79	20	11.92	8	4.77	14	8.34	13	7.75
7	5	Control	6	196.97	3.50	2.10	1.46	6.2	9.2	4.38	4.10	1.95	1.81	0.86	15.00	18	8.57	15	7.14	15	7.14	9	4.29	21	10.00	57	27.14
1	4	Wire	6	207.53	3.09	1.86	1.29	7.1	19.92	10.73	18.20	9.81	9.86	5.31	13.42	14	7.54	10	5.39	16	8.62	4	2.16	2	1.08	48	25.87
1	2	Wire	6	187.79	3.28	1.97	1.37	7.2	17.4	8.85	13.50	6.86	0.00	0.00	No Data	4	2.03	40	20.34	2	1.02	12	6.10	0	0.00	178	90.50
1	5	Wire	6	201.09	3.19	1.91	1.33	7.4	18.6	9.73	15.80	8.27	7.45	3.90	13.50	3	1.57	0	0.00	7	3.66	1	0.52	5	2.62	67	35.06
2	2	Wire	6	169.57	3.20	1.92	1.33	6.5	15.88	8.26	13.10	6.81	6.22	3.23	13.75	6	3.12	6	3.12	5	2.60	20	10.40	3	1.56	81	42.14
2	5	Wire	6	242.58	3.32	1.99	1.38	7.5	2.62	1.32	0.00	0.00	0.00	0.00	0.00	2	1.01	0	0.00	0	0.00	19	9.55	4	2.01	6	3.02
2	6	Wire	6	218.55	3.20	1.92	1.33	7	3.54	1.84	0.34	0.18	0.16	0.08	14.50	2	1.04	1	0.52	3	1.56	18	9.36	4	2.08	41	21.33
3	2	Wire	6	191.46	3.20	1.92	1.33	6.9	24.8	12.90	22.50	11.70	9.49	4.94	14.08	0	0.00	72	37.45	0	0.00	0	0.00	0	0.00	100	52.02
3	3	Wire	6	201.99	3.20	1.92	1.33	6.7	25.22	13.12	23.20	12.07	11.01	5.73	13.50	2	1.04	41	21.33	0	0.00	0	0.00	0	0.00	84	43.70
3	4	Wire	6	207.24	3.28	1.97	1.37	7	24.62	12.52	21.70	11.03	10.20	5.19	13.50	0	0.00	29	14.74	1	0.51	1	0.51	0	0.00	80	40.67
4	1	Wire	6	201.04	3.09	1.86	1.29	6.6	23.26	12.53	21.20	11.42	10.30	5.55	13.50	1	0.54	3	1.62	12	6.47	0	0.00	0	0.00	40	21.56

4	4	Wire	6	197.89	3.15	1.89	1.31	6.8	19.78	10.47	18.10	9.58	7.54	3.99	14.00	0	0.00	21	11.12	0	0.00	0	0.00	0	0.00	23	12.18
4	6	Wire	6	210.61	3.22	1.93	1.34	7	17	8.79	16.40	8.48	7.43	3.84	13.58	4	2.07	1	0.52	2	1.03	0	0.00	2	1.03	9	4.65
5	1	Wire	6	196.12	3.13	1.88	1.30	6.6	15.94	8.49	14.06	7.49	5.45	2.90	15.00	0	0.00	2	1.07	2	1.07	2	1.07	2	1.07	114	60.71
5	2	Wire	6	198.42	3.19	1.91	1.33	6.7	24.34	12.74	22.20	11.62	7.94	4.16	15.07	0	0.00	20	10.46	20	10.46	2	1.05	0	0.00	84	43.95
5	6	Wire	6	229.90	3.33	2.00	1.39	7.6	34.56	17.28	32.30	16.15	12.84	6.42	13.50	1	0.50	5	2.50	5	2.50	7	3.50	1	0.50	54	27.00
6	1	Wire	6	214.19	3.15	1.89	1.31	6.9	4.4	2.33	2.10	1.11	0.77	0.41	14.00	1	0.53	26	13.76	3	1.59	7	3.71	1	0.53	57	30.17
6	4	Wire	6	207.39	3.17	1.90	1.32	6.9	14.7	7.74	12.60	6.63	4.92	2.59	14.00	2	1.05	33	17.37	3	1.58	0	0.00	0	0.00	39	20.52
6	5	Wire	6	217.40	3.22	1.93	1.34	7	10.54	5.45	9.10	4.71	3.47	1.79	14.13	1	0.52	13	6.72	2	1.03	7	3.62	1	0.52	60	31.03
7	2	Wire	6	199.97	2.80	1.68	1.17	6.3	11.66	6.95	9.50	5.66	3.61	2.15	14.58	9	5.36	4	2.38	16	9.54	7	4.17	20	11.92	19	11.32
7	3	Wire	6	192.93	3.07	1.84	1.28	6.3	13.16	7.13	10.00	5.42	3.96	2.15	14.50	34	18.43	12	6.51	8	4.34	2	1.08	66	35.78	36	19.52
7	4	Wire	6	221.92	3.04	1.82	1.27	6.4	11.92	6.54	9.80	5.38	4.33	2.38	14.57	44	24.14	0	0.00	20	10.97	2	1.10	42	23.05	24	13.17
1	1	Small plastic	6	185.59	3.22	1.93	1.34	6.7	13.03	6.74	11.00	5.69	5.00	2.59	14.00	21	10.86	8	4.14	8	4.14	8	4.14	6	3.10	75	38.79
1	5	Small plastic	6	219.07	3.19	1.91	1.33	7.4	20.19	10.56	18.00	9.42	3.20	1.67	14.50	5	2.62	0	0.00	11	5.76	0	0.00	1	0.52	88	46.04
1	3	Small plastic	6	202.76	3.32	1.99	1.38	7.4	10.3	5.18	6.50	3.27	9.34	4.70	13.15	16	8.04	7	3.52	1	0.50	2	1.01	1	0.50	75	37.71
2	1	Small plastic	6	207.00	3.32	1.99	1.38	6.7	31.94	16.06	29.20	14.68	14.01	7.04	13.50	3	1.51	11	5.53	3	1.51	2	1.01	6	3.02	46	23.13
2	3	Small plastic	6	218.87	3.32	1.99	1.38	7.1	44.8	22.52	43.00	21.62	21.09	10.60	13.00	1	0.50	9	4.52	3	1.51	1	0.50	2	1.01	43	21.62
2	5	Small plastic	6	225.63	3.32	1.99	1.38	7.5	3.11	1.56	0.00	0.00	0.00	0.00	0.00	2	1.01	1	0.50	0	0.00	6	3.02	18	9.05	0	0.00
3	3	Small plastic	6	203.32	3.20	1.92	1.33	6.7	24.7	12.85	22.50	11.70	10.47	5.45	14.50	1	0.52	16	8.32	2	1.04	2	1.04	0	0.00	77	40.05
3	5	Small plastic	6	222.28	3.30	1.98	1.37	7.2	24.1	12.18	21.50	10.87	10.38	5.25	13.00	0	0.00	19	9.61	2	1.01	1	0.51	0	0.00	77	38.93
3	6	Small plastic	6	214.57	3.33	2.00	1.39	7.1	8.08	4.04	6.90	3.45	3.17	1.59	13.92	1	0.50	7	3.50	2	1.00	5	2.50	0	0.00	40	20.00
4	2	Small plastic	6	206.40	3.28	1.97	1.37	7	12.24	6.22	9.20	4.68	4.12	2.10	13.00	5	2.54	10	5.08	1	0.51	0	0.00	1	0.51	41	20.85
4	3	Small plastic	6	208.51	3.20	1.92	1.33	6.8	16.06	8.35	14.80	7.70	6.02	3.13	15.00	0	0.00	20	10.40	0	0.00	0	0.00	0	0.00	20	10.40
4	6	Small plastic	6	211.92	3.22	1.93	1.34	7	14.88	7.70	14.20	7.34	6.14	3.18	14.00	1	0.52	0	0.00	5	2.59	0	0.00	1	0.52	7	3.62
5	1	Small plastic	6	192.52	3.13	1.88	1.30	6.6	14.28	7.60	11.80	6.28	4.61	2.46	14.00	4	2.13	10	5.33	2	1.07	0	0.00	4	2.13	82	43.67
5	3	Small plastic	6	209.74	3.24	1.94	1.35	6.8	38.06	19.57	37.00	19.03	13.56	6.97	14.00	0	0.00	5	2.57	1	0.51	0	0.00	0	0.00	50	25.71
5	5	Small plastic	6	204.41	3.20	1.92	1.33	7	61.12	31.79	60.10	31.26	24.62	12.81	13.64	0	0.00	2	1.04	0	0.00	9	4.68	1	0.52	36	18.73
6	2	Small plastic	6	173.32	3.22	1.93	1.34	7.2	9.46	4.89	8.40	4.34	2.98	1.54	14.50	0	0.00	17	8.79	1	0.52	2	1.03	0	0.00	31	16.03
6	4	Small plastic	6	206.23	3.17	1.90	1.32	6.9	16.62	8.75	14.20	7.47	4.91	2.58	14.00	2	1.05	18	9.47	7	3.68	0	0.00	0	0.00	39	20.52
6	6	Small plastic	6	206.78	3.26	1.96	1.36	7.1	8.28	4.23	7.20	3.68	2.94	1.50	12.50	0	0.00	29	14.83	5	2.56	2	1.02	0	0.00	45	23.01
7	1	Small plastic	6	222.05	3.61	2.17	1.50	6.1	13.6	6.28	9.50	4.38	3.70	1.71	15.00	33	15.23	18	8.31	21	9.69	57	26.31	57	26.31	45	20.77
7	3	Small plastic	6	206.94	3.07	1.84	1.28	6.3	11.2	6.07	8.40	4.55	3.27	1.77	13.92	26	14.10	5	2.71	10	5.42	2	1.08	39	21.14	20	10.84
7	6	Small plastic	6	217.77	3.15	1.89	1.31	6.3	5.68	3.01	2.40	1.27	0.98	0.52	14.00	3	1.59	10	5.29	10	5.29	2	1.06	3	1.59	37	19.59

1	6	Large plastic	6	183.23	3.30	1.98	1.37	7.2	16.12	8.15	14.50	7.33	6.78	3.43	15.00	7	3.54	0	0.00	15	7.58	4	2.02	5	2.53	2	1.01
1	1	Large plastic	6	205.67	3.22	1.93	1.34	6.7	13.07	6.76	11.50	5.95	4.92	2.54	14.00	9	4.65	3	1.55	4	2.07	1	0.52	7	3.62	40	20.69
1	4	Large plastic	6	212.68	3.09	1.86	1.29	7.1	15.8	8.51	14.00	7.54	6.48	3.49	13.50	5	2.69	0	0.00	5	2.69	5	2.69	0	0.00	56	30.18
2	2	Large plastic	6	207.57	3.20	1.92	1.33	6.5	13.96	7.26	11.20	5.83	5.61	2.92	13.75	6	3.12	2	1.04	3	1.56	1	0.52	0	0.00	27	14.05
2	3	Large plastic	6	218.89	3.32	1.99	1.38	7.1	45.6	22.93	44.30	22.27	23.10	11.61	12.50	1	0.50	15	7.54	4	2.01	0	0.00	2	1.01	25	12.57
2	4	Large plastic	6	199.21	3.48	2.09	1.45	6.7	2.49	1.19	0.35	0.17	0.15	0.07	14.00	5	2.39	0	0.00	0	0.00	2	0.96	8	3.83	1	0.48
3	1	Large plastic	6	210.71	3.19	1.91	1.33	6.7	16.42	8.59	14.50	7.59	6.27	3.28	14.50	0	0.00	32	16.74	2	1.05	1	0.52	1	0.52	32	16.74
3	4	Large plastic	6	213.30	3.28	1.97	1.37	7	18.22	9.26	16.50	8.39	7.21	3.67	14.00	0	0.00	20	10.17	1	0.51	0	0.00	0	0.00	32	16.27
3	6	Large plastic	6	196.57	3.33	2.00	1.39	7.1	7.26	3.63	5.90	2.95	2.54	1.27	15.00	1	0.50	2	1.00	1	0.50	0	0.00	0	0.00	19	9.50
4	1	Large plastic	6	205.62	3.09	1.86	1.29	6.6	19.54	10.53	18.60	10.02	9.24	4.98	13.00	0	0.00	6	3.23	7	3.77	0	0.00	0	0.00	12	6.47
4	3	Large plastic	6	200.04	3.20	1.92	1.33	6.8	18.72	9.74	17.80	9.26	7.65	3.98	13.92	1	0.52	3	1.56	1	0.52	1	0.52	0	0.00	20	10.40
4	5	Large plastic	6	217.39	3.32	1.99	1.38	7.1	18.4	9.25	17.20	8.65	7.76	3.90	13.00	0	0.00	7	3.52	1	0.50	0	0.00	0	0.00	13	6.54
5	3	Large plastic	6	206.26	3.24	1.94	1.35	6.8	49.6	25.51	48.50	24.94	18.76	9.65	14.50	0	0.00	9	4.63	5	2.57	1	0.51	4	2.06	42	21.60
5	4	Large plastic	6	218.15	3.22	1.93	1.34	7	36.3	18.77	34.10	17.64	13.85	7.16	13.50	1	0.52	2	1.03	11	5.69	0	0.00	0	0.00	31	16.03
5	6	Large plastic	6	221.01	3.33	2.00	1.39	7.6	35.86	17.93	35.20	17.60	14.41	7.20	15.00	3	1.50	0	0.00	2	1.00	11	5.50	0	0.00	35	17.50
6	2	Large plastic	6	192.34	3.22	1.93	1.34	7.2	10.23	5.29	8.35	4.32	2.93	1.52	15.57	1	0.52	8	4.14	3	1.55	5	2.59	0	0.00	23	11.90
6	3	Large plastic	6		3.09	1.86	1.29	6.8	11.32	6.10	10.00	5.39	3.73	2.01	14.00	0	0.00	5	2.69	3	1.62	1	0.54	0	0.00	21	11.32
6	5	Large plastic	6	203.63	3.22	1.93	1.34	7	10.76	5.57	9.20	4.76	3.49	1.80	15.00	4	2.07	8	4.14	8	4.14	3	1.55	1	0.52	31	16.03
7	4	Large plastic	6	214.49	3.04	1.82	1.27	6.4	11.32	6.21	9.40	5.16	3.70	2.03	14.64	15	8.23	0	0.00	13	7.13	1	0.55	29	15.91	9	4.94
7	5	Large plastic	6	201.79	3.50	2.10	1.46	6.2	8.08	3.85	3.80	1.81	1.48	0.71	14.00	5	2.38	3	1.43	14	6.67	3	1.43	22	10.48	17	8.09
7	6	Large plastic	6	207.78	3.15	1.89	1.31	6.3	6.02	3.19	2.30	1.22	1.07	0.57	13.67	1	0.53	19	10.06	17	9.00	1	0.53	0	0.00	23	12.18

Table S2. Operational data, from sensors (load cells, GPS, and NOTUS), and catch statistics from experiment 2—testing a SAFE on an otter trawl.

																Number											
Day no	**Haul**	**Treatment**	**Wing-end spread**	**Trawl load (kg)**	**Distance trawled (km)**	**Wing-end area trawled (Ha)**	**Average speed (m/sec)**	**Paired fuel used (L)**	**Total catch Weight 40-min**	**Total catch weight Ha^{-1}**	**Weight School prawns 40-min**	**Weight School prawns Ha^{-1}**	**No. School prawns 40-min**	**No. School prawns Ha^{-1}**	**CI School prawns**	**Yellowfin bream 40-min**	**Yellowfin bream Ha^{-1}**	**Ramsey's perchlet 4-min**	**Ramsey's perchlet Ha^{-1}**	**Southern herring 40-min**	**Southern herring Ha^{-1}**	**Silver biddy 40-min**	**Silver biddy Ha^{-1}**	**Tailor 40-min**	**Tailor Ha^{-1}**	**Tarwhine 40-min**	**Tarwhine Ha^{-1}**
1	1	Control	4.28	251.42	3.20	1.37	1.33	9.7	17.50	12.78	16.80	12.27	6641.97	4849.24	15.32	0	0.00	4	2.92	1	0.73	0	0.00	15	10.95	0	0.00
1	2	Control	4.24	275.44	3.15	1.34	1.31	10.2	15.40	11.53	14.00	10.48	5230.77	3916.47	15.68	0	0.00	15	11.23	1	0.75	0	0.00	41	30.70	0	0.00
2	1	Control	4.85	257.32	3.17	1.54	1.32	10.2	4.68	3.05	3.90	2.54	1516.59	987.39	14.49	1	0.65	5	3.26	1	0.65	0	0.00	26	16.93	0	0.00
2	2	Control	3.79	238.22	3.13	1.19	1.30	10	4.76	4.01	4.40	3.70	1730.74	1457.32	15.34	6	5.05	2	1.68	0	0.00	1	0.84	8	6.74	0	0.00
2	3	Control	4.88	261.43	3.19	1.55	1.33	10.1	5.40	3.48	4.10	2.64	1542.70	993.22	14.63	0	0.00	5	3.22	0	0.00	0	0.00	14	9.01	0	0.00
2	4	Control	5.05	263.27	3.19	1.61	1.33	10	7.20	4.48	6.24	3.88	2216.87	1378.10	16.03	1	0.62	3	1.86	0	0.00	0	0.00	18	11.19	0	0.00
2	5	Control	4.31	251.65	3.26	1.41	1.36	9.8	5.45	3.88	4.50	3.20	1783.71	1269.52	14.30	2	1.42	5	3.56	0	0.00	0	0.00	11	7.83	0	0.00
2	6	Control	4.16	264.86	3.24	1.35	1.35	10.5	15.80	11.73	14.30	10.62	5677.00	4215.12	14.37	2	1.48	6	4.45	1	0.74	0	0.00	33	24.50	1	0.74
3	1	Control	4.08	277.29	3.54	1.44	1.47	11.3	18.38	12.74	15.30	10.60	5608.66	3887.20	15.76	13	9.01	14	9.70	48	33.27	22	15.25	28	19.41	8	5.54
3	2	Control	4.74	210.92	3.20	1.52	1.33	9.7	3.52	2.32	0.42	0.28	154.17	101.52	14.81	2	1.32	6	3.95	116	76.38	8	5.27	8	5.27	10	6.58
3	3	Control	4.56	236.94	3.35	1.53	1.40	9.3	2.52	1.65	1.16	0.76	442.28	289.27	14.64	3	1.96	10	6.54	8	5.23	0	0.00	30	19.62	1	0.65
3	4	Control	3.66	276.96	3.20	1.17	1.33	9.7	2.64	2.25	1.28	1.09	453.68	387.18	14.97	4	3.41	3	2.56	24	20.48	2	1.71	6	5.12	3	2.56
3	5	Control	4.25	247.00	2.85	1.21	1.19	9.6	18.90	15.59	16.80	13.86	5861.64	4835.81	16.13	3	2.47	12	9.90	8	6.60	17	14.02	23	18.97	6	4.95
3	6	Control	4.16	274.50	3.76	1.56	1.57	12.4	16.54	10.58	13.50	8.64	4300.71	2751.74	15.53	4	2.56	3	1.92	4	2.56	17	10.88	8	5.12	5	3.20
4	1	Control	4.01	263.03	3.35	1.34	1.40	9.8	14.92	11.10	6.50	4.84	2173.34	1616.83	15.28	16	11.90	250	185.98	48	35.71	0	0.00	112	83.32	22	16.37
4	2	Control	4.77	245.34	3.26	1.56	1.36	10	15.60	10.03	10.70	6.88	3548.54	2281.64	16.39	16	10.29	23	14.79	0	0.00	11	7.07	25	16.07	1	0.64
4	3	Control	4.54	245.61	3.20	1.45	1.33	10.3	14.00	9.63	8.50	5.85	2988.09	2055.67	16.05	19	13.07	40	27.52	3	2.06	15	10.32	19	13.07	0	0.00
4	4	Control	4.06	269.57	3.26	1.32	1.36	10.1	10.68	8.07	6.80	5.14	2415.61	1824.50	16.04	10	7.55	43	32.48	0	0.00	21	15.86	47	35.50	6	4.53
4	5	Control	4.76	264.85	3.28	1.56	1.37	9.8	29.00	18.60	24.00	15.40	7609.02	4881.05	15.64	2	1.28	96	61.58	0	0.00	12	7.70	30	19.24	2	1.28
4	6	Control	3.92	261.88	3.28	1.28	1.37	9.9	39.54	30.78	33.80	26.31	12315.95	9586.79	15.87	5	3.89	53	41.26	1	0.78	11	8.56	20	15.57	4	3.11
5	1	Control	4.41	261.44	3.70	1.63	1.54	10.6	2.00	1.22	0.12	0.07	37.55	22.98	16.69	17	10.40	13	7.96	1	0.61	27	16.53	5	3.06	21	12.85
5	2	Control	4.52	242.86	3.00	1.36	1.25	10.7	3.84	2.83	0.30	0.22	111.39	82.12	15.86	14	10.32	22	16.22	3	2.21	14	10.32	8	5.90	16	11.80
5	3	Control	3.99	278.39	3.32	1.32	1.38	10.9	1.74	1.32	0.52	0.39	218.46	165.34	14.11	13	9.84	6	4.54	7	5.30	0	0.00	7	5.30	1	0.76
5	4	Control	4.10	270.84	3.26	1.34	1.36	10.3	2.24	1.68	1.70	1.27	658.77	492.95	15.37	3	2.24	2	1.50	2	1.50	0	0.00	12	8.98	0	0.00
5	5	Control	4.36	274.50	3.41	1.49	1.42	10.5	0.84	0.56	0.10	0.07	42.80	28.78	15.24	3	2.02	6	4.03	7	4.71	3	2.02	11	7.40	2	1.34
5	6	Control	4.60	266.93	3.30	1.52	1.37	10.4	1.08	0.71	0.14	0.09	59.04	38.93	14.05	3	1.98	7	4.62	5	3.30	7	4.62	14	9.23	6	3.96
1	1	Treatment	4.02	263.79	3.20	1.29	1.33	9.7	14.10	10.94	13.40	10.39	5118.00	3969.87	15.57	0	0.00	4	3.10	0	0.00	0	0.00	4	3.10	0	0.00
1	2	Treatment	4.46	265.76	3.20	1.43	1.33	10.2	12.36	8.66	11.50	8.05	4776.28	3344.62	15.12	1	0.70	7	4.90	0	0.00	1	0.70	8	5.60	0	0.00
2	1	Treatment	4.19	255.31	3.17	1.33	1.32	10.2	5.00	3.77	4.30	3.24	1687.34	1271.61	15.33	4	3.01	15	11.30	1	0.75	0	0.00	22	16.58	1	0.75
2	2	Treatment	4.89	251.44	3.13	1.53	1.30	10	5.82	3.80	4.88	3.19	1941.07	1268.25	15.31	6	3.92	4	2.61	0	0.00	0	0.00	19	12.41	1	0.65
2	3	Treatment	3.84	268.39	3.19	1.22	1.33	10.1	5.20	4.25	4.40	3.60	1735.69	1418.97	15.38	0	0.00	6	4.91	0	0.00	2	1.64	13	10.63	0	0.00
2	4	Treatment	3.97	262.72	3.19	1.26	1.33	10	5.60	4.43	4.60	3.64	1783.30	1411.34	15.48	0	0.00	3	2.37	0	0.00	0	0.00	9	7.12	0	0.00

2	5	Treatment	4.59	262.23	3.26	1.50	1.36	9.8	6.70	4.48	5.30	3.54	2315.29	1547.37	14.79	3	2.00	6	4.01	0	0.00	0	0.00	39	26.06	0	0.00
2	6	Treatment	4.45	255.67	3.24	1.44	1.35	10.5	15.18	10.52	13.80	9.56	5770.92	3999.21	15.04	4	2.77	3	2.08	0	0.00	0	0.00	9	6.24	0	0.00
3	1	Treatment	4.07	258.27	3.54	1.44	1.47	11.3	17.92	12.46	16.10	11.19	6358.13	4419.94	15.43	7	4.87	11	7.65	20	13.90	11	7.65	12	8.34	3	2.09
3	2	Treatment	3.97	256.50	3.20	1.27	1.33	9.7	1.76	1.39	0.30	0.24	108.08	85.08	16.01	1	0.79	20	15.74	1	0.79	16	12.59	5	3.94	3	2.36
3	3	Treatment	4.20	263.32	3.35	1.41	1.40	9.3	2.28	1.62	1.24	0.88	485.13	344.58	15.40	1	0.71	9	6.39	9	6.39	0	0.00	25	17.76	0	0.00
3	4	Treatment	4.17	267.50	3.20	1.34	1.33	9.7	2.22	1.66	1.34	1.00	490.64	367.37	15.78	2	1.50	4	3.00	11	8.24	5	3.74	7	5.24	3	2.25
3	5	Treatment	3.36	263.77	2.85	0.96	1.19	9.6	12.14	12.67	10.50	10.96	3415.21	3563.83	16.41	5	5.22	9	9.39	7	7.30	8	8.35	9	9.39	3	3.13
3	6	Treatment	4.34	257.53	3.76	1.63	1.57	12.4	18.30	11.22	14.90	9.13	5313.60	3256.58	16.02	3	1.84	7	4.29	5	3.06	14	8.58	19	11.64	5	3.06
4	1	Treatment	4.40	230.97	3.35	1.47	1.40	9.8	12.20	8.27	6.40	4.34	2376.61	1611.34	15.76	16	10.85	64	43.39	4	2.71	52	35.26	72	48.82	20	13.56
4	2	Treatment	3.71	278.39	3.26	1.21	1.36	10	17.58	14.55	7.60	6.29	2565.13	2123.56	16.27	17	14.07	40	33.11	0	0.00	19	15.73	7	5.79	4	3.31
4	3	Treatment	3.66	262.81	3.20	1.17	1.33	10.3	14.22	12.13	8.60	7.34	3207.72	2737.03	15.77	24	20.48	54	46.08	1	0.85	22	18.77	0	0.00	2	1.71
4	4	Treatment	4.79	240.91	3.26	1.56	1.36	10.1	7.80	5.00	5.00	3.21	1777.43	1139.61	15.97	13	8.34	21	13.46	0	0.00	13	8.34	10	6.41	3	1.92
4	5	Treatment	3.58	257.45	3.28	1.17	1.37	9.8	31.04	26.45	28.00	23.86	10460.73	8913.83	15.74	8	6.82	57	48.57	0	0.00	33	28.12	26	22.16	1	0.85
4	6	Treatment	4.39	264.29	3.28	1.44	1.37	9.9	29.50	20.50	27.00	18.77	9077.44	6309.50	16.32	3	2.09	18	12.51	0	0.00	9	6.26	13	9.04	4	2.78
5	1	Treatment	3.61	273.24	3.70	1.34	1.54	10.6	2.62	1.96	0.12	0.09	37.71	28.20	16.67	19	14.21	16	11.97	6	4.49	18	13.46	7	5.24	19	14.21
5	2	Treatment	3.55	255.77	3.00	1.06	1.25	10.7	1.88	1.77	0.18	0.17	68.17	64.09	15.74	6	5.64	1	0.94	5	4.70	30	28.21	0	0.00	4	3.76
5	3	Treatment	4.48	259.32	3.32	1.48	1.38	10.9	1.66	1.12	0.50	0.34	201.07	135.54	15.31	6	4.04	10	6.74	0	0.00	0	0.00	8	5.39	1	0.67
5	4	Treatment	4.70	238.64	3.26	1.53	1.36	10.3	2.34	1.53	1.60	1.05	609.03	397.97	15.47	9	5.88	7	4.57	0	0.00	0	0.00	4	2.61	1	0.65
5	5	Treatment	4.40	258.01	3.41	1.50	1.42	10.5	0.82	0.55	0.10	0.07	41.47	27.66	15.34	3	2.00	5	3.33	7	4.67	4	2.67	3	2.00	3	2.00
5	6	Treatment	3.38	278.30	3.30	1.11	1.37	10.4	0.82	0.74	0.16	0.14	54.24	48.66	16.35	5	4.49	3	2.69	3	2.69	2	1.79	8	7.18	6	5.38

Appendix 4. McHugh, M. J., Broadhurst, M. K., Sterling, D. J. and Millar, R. B. (2015) Comparing three conventional penaeid-trawl otter boards and the new batwing design. *Fisheries Research* **167**: 180−189.

Comparing three conventional penaeid-trawl otter boards and the new batwing design

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Abstract

Three experiments were conducted to compare the engineering and catching performances of a hydrodynamic otter board termed the ‘batwing’ (comprising a sled-and-sail assembly, configured to operate at 20^{o} angle of attack—AOA and with minimal bottom contact) against three conventional designs (termed the ‘flat-rectangular’; ‘kilfoil’ and ‘cambered’ otter boards) with AOAs between ~30 and 40^{o}. Experiments involved paired penaeid trawls (7.35-m headlines). The first experiment compared the batwing otter boards against all other designs (using 41-mm mesh trawls). In experiment 2, the batwing was tested against the flat-rectangular design (with 32-mm mesh trawls). In experiment 3, the batwing and flat-rectangular otter boards were towed without trawls to facilitate estimates of their partitioned drag. Overall, compared to the conventional otter boards, the batwings had up to ~86 and 18% less bottom contact and drag, respectively. Among the conventional otter boards, the trawls spread by the cambered design caught up to 13% more school prawns *Metapenaeus macleayi*; attributed to their greater solid profile. No significant differences were detected among catches of fish in the trawls spread by the various otter boards. The results reaffirm that because otter boards contribute towards a large proportion of total system drag (estimated here at up to ~56%), their appropriate configuration is essential to maximise the fuel efficiency of penaeid-trawl systems.

Keywords: drag, fuel reduction, habitat impacts, otter-board design, penaeids,

1. Introduction

Penaeids are targeted throughout the world's tropical and temperate regions; mostly using small fishing vessels (<25 m) towing multi-net trawl systems that are laterally spread by paired hydro vanes, called 'otter boards' (Kelleher, 2005; Gillett, 2008). While there is considerable variety among otter-board designs, all encompass a substantial proportion of the entire trawling system weight to ensure sufficient seabed contact, and are orientated at an angle to the tow direction (termed the angle of attack—AOA). The water moving over otter boards creates hydrodynamic forces that horizontally open penaeid trawls to spread ratios (SR) typically 0.6 to 0.8 of their total headline length. The drag component of such hydrodynamic forces has been hypothesised to account for up to 30% of the total-system drag (Sterling, 2000).

At a broad level, the most common otter boards are simple flat, rectangular designs—although more hydrodynamically complex cambered variations are also popular (Seafish et al., 1993). Irrespective of design subtleties, the majority of otter boards are rigged to have AOAs between 30 and 40° (Seafish et al., 1993; Sterling, 2000). Operating conventional otter boards at such high AOAs helps to maintain their stability, which keeps the other trawl components at optimal efficiency (Patterson and Watts, 1985). Even slight reductions in AOA below this range can result in operational issues, manifesting as reduced stability and possibly lost effective fishing time (Patterson and Watts, 1985; Seafish et al., 1993). In an attempt to overcome such issues, a more recent prototype termed the 'batwing' otter board was developed by Sterling and Eayrs (2010) to remain at a constant 20°AOA, and with robust stability achieved through its unique rigging strategy (see Methods).

Although not extensively quantified (but see Patterson and Watts, 1985; 1986), compared to conventional designs, otter boards such as the batwing that have low AOAs should have relatively lower drag for the same spreading force and therefore require less fuel to tow. Calculating the extent of any such fuel reductions is complex. It is well established that the fuel consumed during trawling is proportional to the thrust applied by the trawler, if propeller efficiency remains constant (Prado, 1990). However, the assumption of a proportional relationship between drag reductions and fuel savings remains approximate because many factors affect efficiency, including propeller loading.

Globally, it is becoming imperative to reduce fuel usage in many fisheries including demersal trawling, which has some of the greatest fuel-to-catch ratios, with fuel accounting for 30% of a trawl operator's total costs in developed countries (Suuronen et al., 2012). In fact, in Australia, trawlers use at least 55% of their fuel while trawling (with the rest used during travelling between trawl grounds and operating electrical equipment), and are operating close to their profitability threshold (Thomas et al., 2010; Wakeford, 2010).

Beyond drag/fuel savings, a potential concomitant benefit of lowering otter-board AOA is reduced benthic contact for any given length (i.e. ∼1.5% for each degree the AOA is lowered), and subsequently fewer associated impacts. For example, an otter board ~1 m long deployed at 40° AOA will impact the bottom for ~64 cm, while at 20° its contact will be reduced to ~34 cm. Even slight reductions in impacts are potentially beneficial, considering that otter boards leave the most discernible track marks from trawl configurations (Caddy, 1973; Kaiser et al., 2002). However, from a catching perspective, one concern with minimising otter-board bottom contact is that a lower AOA could reduce substrate disturbance and negatively affect catches because penaeids mostly reside in the substratum (Broadhurst et al., 2012; 2013a; McHugh et al., 2014). Further, otter boards are known to herd fish (Wardle, 1989), either through visual or tactile stimuli, and so even subtle variation in their design and AOA might influence species selection by the trawl.

Despite the above, there have been very few formal studies of the effects of otter boards on the engineering (e.g. AOA and spreading force) and catching performances of penaeid trawls (but see Broadhurst et al., 2012; 2013b). The main aim of this study was to address this shortfall by quantifying the catches and fuel efficiency (measured as least drag) associated with three conventional otter-board designs and the batwing (with its relatively less bottom contact) in one Australian fishery targeting school prawns, *Metapenaeus macleayi*. A secondary aim was to use an approach involving removing the trawls and just towing the otter boards (separated by wire stays) to quantify their contribution towards total system drag for the tested trawls, so the benefits of future refinements to otter-board design and their AOAs can be established.

2. Methods

Three experiments were completed in the Clarence River, New South Wales, Australia, during May 2013 using a local penaeid trawler (10 m and 89-kw) fishing in ∼4–18 m water-depth across mud and sand substratum. The trawler had 8-mm diameter (Ø) stainless warps and 40-m bridles (6-mm Ø stainless wire) on a double-drum, hydraulic split winch. The trawler was also equipped with: a fuel monitor (Floscan series 9000); global positioning system (GPS; Lowrance); hull-mounted sum log (EchoPilot, Bronze Log+), warp-attachable load cells and associated data logger (Amalgamated Instrument Company; model nos PA6139 and TP4); and a portable acoustic, trawl-monitoring system with paired wing-end distance sensors (Notus Trawlmaster System; Model no. TM800ET; see Broadhurst et al., 2013a for details). All monitoring equipment was calibrated prior to starting the experiments.

2.1. Trawls and otter boards tested

Four trawls were constructed—two identical replicates of two similar designs (Fig. 1). The first two trawls (termed A and B) were conventionally mandated designs for the fishery, and comprised a mean stretched mesh opening (SMO) ± SE of 41.43 ± 0.11 mm (n = 20 meshes in each trawl) and 1.2-mm Ø twine, with a side taper of 1N3B and were used in experiment 1 (Fig. 1). Owing to the small sizes of prawns encountered (see Results), the third and fourth trawls (labelled C and D) used in experiment 2 were made from smaller 31.61 ± 0.08 mm SMO (n = 20 meshes in each trawl) and 0.8 mm Ø twine, and with a side taper of 1N5B (Fig. 1). All four trawls were rigged with identical Nordmøre-grids and square-mesh codends made from 27.37 ± 0.10-mm SMO (n = 20 meshes in each trawl) polyamide mesh hung on the bar and had 2.89-m sweeps (6-mm Ø wire) attached at their wing ends, terminating in snap clips to facilitate attachment to the otter boards.

Four otter-board pairs were tested, all with 100 mm base plates (Fig. 2). The first otter board represented a standard design used nationally and internationally, and comprised a mild-steel frame with marine-grade plywood inserts and was termed the ‘flat-rectangular’ (52.5 kg, 1.39 × 0.61 m, solid area of 0.77m^2; Fig. 2a). The second design (‘kilfoil’) was constructed entirely from galvanized mild steel and had three 270 mm-wide cambered vertical foils in a rectangular frame (63.0 kg, 1.25 × 0.63 m, solid area of 0.58 m^2; Fig. 2b), while the third (‘cambered’) had a single, cambered foil over its entire length and was made from stainless-steel plate (53.0 kg, 1.08 × 0.73 m, 0.79 m^2; Fig. 2c).

The fourth design was the batwing and comprised a main sled made from mild and stainless steel, and a polyurethane (PU) sail set on a stainless-steel boom and mast (60.7 kg, 1.12 × 1.23 m, 0.74 m^2) configured to remain at a 20° AOA (Fig. 2d). The batwing foil was designed to act like an independent kite with a single longitudinal connection to the trawl system via a heavy main sled made from a combination of mild and stainless steel (Fig. 2d). The batwing was configured so that the heavy sled baseplate was aligned to the tow direction, while the sail had a stable AOA and rode on a polyurethane flap designed to pass lightly over the seabed on a layer of pressurised water (similar in concept to the skirt on a hovercraft).

To ensure the same trawl wing-end height during fishing, vertical upper sweep attachment bars were welded to the tops of the flat-rectangular and kilfoil designs to match the heights of the cambered and batwing otter boards (Fig. 2). All otter boards were rigged at their industry-standard AOAs, and to achieve the same trawl wing-end spreads (see Results).

2.2. Experiment 1−four pairs of otter boards with trawls

In the first experiment, the four otter boards were tested against each other in paired comparisons. On each fishing day, one of the six possible otter-board combinations was attached to each side of the vessel. The 41-mm trawls (A and B) and sweeps were clipped to the otter boards, while the Notus paired sensors were attached to the trawl wing ends. After two replicate deployments, the trawl-monitoring equipment (Notus sensors and load cells) were swapped from side-to-side, but the trawls remained. After four replicate deployments, both the trawls and the trawl-monitoring equipment were swapped from side-to-side. After six deployments, just the trawl-monitoring equipment was swapped again. In total, each of the four otter-board pairs were deployed across three alternate replicate days, with eight replicate 30-min deployments for each treatment on each day (providing a total of 24 deployments).

2.3. Experiment 2−two pairs of otter boards with trawls

To obtain more data over a broader range of conditions (and especially longer tow durations more representative of conventional operations), just the flat-rectangular and batwing otter boards were compared. On each of four days, pairs of the two otter boards were alternately attached to each side of the vessel, and clipped to the sweeps attached to the 31-mm trawls. The smaller-mesh trawls were used to remove the possibility that confounding distortion of the trawls (particularly in the side panels) caused by the strain-equalizing mechanism of the batwing otter boards allowed small school prawns to escape (see Results and Discussion). The trawl monitoring equipment was randomly allocated to one side of the vessel on each day. Five 50-min deployments were completed on each day (i.e. a total of 20 deployments for each otter board), swapping the trawls from side-to-side after the third deployment.

2.4. Experiment 3−two pairs of otter boards without trawls

In experiment 3, the flat-rectangular and batwing otter boards were again tested against each other as for experiment 2, but with the trawls removed to obtain drag estimates for the otter boards only. To limit separation of the otter boards and fix the AOA, two lengths of 3-m stainless steel wire (6-mm Ø) were secured between the upper and lower net attachment points on each otter board pair and a third wire (3.5 m) was connected between each otter-board pair at the warp connection points (Fig. 3). The trawl monitoring equipment was alternately allocated to one side of the vessel on each day (with the Notus paired sensors secured to the outside posterior surface of each otter board; Fig. 3) and between 8 and 12 replicate deployments completed over four days (total n = 40).

2.5. Data collected and statistical analyses

In all three experiments, the technical data collected describing the operational procedures during each deployment included the: (i) drag (kgf) of each gear configuration; (ii) total distance the gears were towed (otter boards on and off the bottom—obtained from the plotter and trawl-monitoring system); (iii) speed over the ground (SOG) and through the water (STW; both in ms^{-1}), (iv) water depth (m), (v) distance of the gear configurations behind the vessel, and (vi) wing-end (experiments 1 and 2) or otter-board (experiment 3) spreads (m). All electronic data were recorded at 60-s intervals. For experiments 1 and 2, otter-board AOA was estimated using the otter-board orientation model of Sterling (2000) with inputs of wing-end spread (for each deployment) and used to calculate otter-board span (contact) on the substrate (by multiplying the otter-board length by the sine of the AOA) and ultimately, the effective total bottom contact (average wing-end spread + otter-board lateral base-plate contact).

At the end of each deployment in experiments 1 and 2, all catches were separated by codend, with the total weights of school prawns and bycatch collected along with the numbers of each bycatch species. Total lengths (TL to the nearest 0.5 mm) of the most abundant teleosts were also collected. A random sample of ~500 g of school prawns was collected and a subsample (~100) measured (carapace length–CL in mm) in the laboratory. These data were used to estimate the total numbers caught and mean CL during each deployment.

The technical and biological data were separately analysed within experiments using linear mixed models (LMMs), with some standardised prior to analyses. Numbers and weights were analysed as log-transformed data, after being standardised to per ha trawled calculated using the foot-rope contact (average wing-end spread × distance trawled) and, additionally where these were significant for school prawns, the effective total-system contact ((i.e. wing-end spread + span of otter-board contact) × the distance trawled) for fishing. The latter was done to test the hypothesis that otter-board contact span explained some of the variability in school prawn catches (see Results), and did not include the batwing sleds, because these were outside the effective herding path of the trawl (Broadhurst et al., 2012). All other data, including the mean CL of school prawns per deployment, drag, wing-end spread, SOG, STW and distance trawled were analysed in their raw form.

All models included ‘otter-board pair’ as a fixed effect while, where appropriate (depending on the experiment), the random effects included ‘trawls’, ‘trawl sides’, ‘otter-board sides’ and ‘days’ and the interaction between ‘deployments’ and days. For the LMMs assessing drag and spread, additional random terms involved load cells and the paired Notus sensors, respectively while additional covariates included SOG, ‘current’ (calculated as the speed of the water in the direction of travel and defined as SOG–STW), distance aft of the trawl configuration from the vessel and fishing depth. All models were fitted using the lmer function from the lme4 package in R 2.15.3 (The R Project for Statistical Computing; http://www.r-project.org/) and the significance of trawl design was determined using a likelihood ratio test (LRT). The LRT was used to compare model log-likelihoods and test whether any differences were statistically significant (Rice, 2006). In experiment 1, where the levels of otter-board pair exceeded two, significant differences were explored using the Benjamini-Hochberg-Yekutieli procedure to control the false discovery rate (FDR; Benjamini and Yekutieli, 2001). The FDR is the expected proportion of false positive discoveries between all of the rejected hypotheses.

Relevant back-transformed predicted means from the LMMs were used to calculate relative fuel consumptions associated with towing the trawls and otter boards in experiments 1 and 2. Specifically, assuming that for any given towing speed, the concomitant fuel usage was proportional to the drag, it is possible to determine relative fuel consumption rate (L h^{-1}) between each side using the predicted mean drags as determined by the repeated load-cell measurements. Fuel consumption was standardised to per ha trawled (i.e. intensity) and per kg of school prawns caught for each otter-board configuration by comparing the predicted fuel consumption rate with predicted mean wing-end spread (the rate at which area was being swept for a given trawl speed), and the predicted absolute mean school prawn catches (derived by fitting the same model above to the unstandardized log-transformed data) from the respective LMMs.

3. Results

School prawns comprised 99% of the total catches in experiments 1 and 2 (Table 1). The minimal bycatch included 25 species, but was dominated by forktail catfish (*Arius graeffei*; 8.0–13.5 cm TL), southern herring (*Herklotsichthys castelnaui*; 7.0–16.0 cm TL) and mulloway (*Argyrosomus japonicas*; 4.5–20.5 cm TL) in experiment 1 (80% of the total catch) and yellowfin bream (*Acanthopagrus australis*; 6.5–23.5 cm TL) and southern herring (7.0–15.5 cm TL) in experiment 2 (64%) (Table 1).

3.1. Experiment 1−four pairs of otter boards with trawls

The four otter-board and trawl configurations were towed at (mean ± SE) SOG of 1.24 ± 0.01 ms^{-1} and STWs of 1.43 ± 0.08 ms^{-1}. There was no significant difference in the wing-end spreads of the trawls rigged among otter-board pairs, nor distance trawled (LMM, $p > 0.05$; Tables 2 and 3), but otter-board AOAs, total bottom contact and drag were all significantly different (LMMs, $p < 0.01$; Tables 2 and 3). Specifically, while the batwing maintained a 20° AOA, the kilfoil (30.58 ± 0.04°), flat-rectangular (32.83 ± 0.04°) and cambered (38.62 ± 0.04°) designs were spread at significantly (and incrementally) greater AOAs (FDR, $p < 0.05$; Tables 2 and 3). However, the AOAs did not significantly affect the total bottom contact (because the different otter-board lengths offset any relative reductions) among the conventional configurations (FDR, $p > 0.05$; Tables 2 and 3), but all three had significantly greater total bottom contacts than the batwing configuration (up to 1.24 times more; FDR, $p < 0.05$; Table 3). For individual otter boards (from the four designs), a combination of their AOA and length altered (by up to 66%) their projected surface area to between ~0.25 and ~0.48 m^2.

The LMM for drag included the fixed effects of otter-board pair, SOG and current, with the former two being significant ($p < 0.05$). To facilitate presentation, the predicated mean drags were calculated at the centred value of SOG (i.e. drag at average SOGs) and for zero current (Table 3). Compared to all three conventional systems, the batwing configuration had significantly less drag (predicted mean reduced by between 14.00 and 18.34%). Further, compared to the kilfoil and cambered otter-board configurations (which had the same drag; FDR, $p > 0.05$; Table 3), there was less drag associated with the flat-rectangular configuration (by 5%; FDR, $p < 0.05$; Table 3). The fuel rate varied between ~5.00 and ~6.13 L h^{-1} while fuel intensity was between ~2.20 and ~2.68 L ha^{-1}, with the batwing otter boards requiring the least fuel to tow (Table 3).

For the biological variables, significant differences were limited to school prawn catches, with the most consistent difference being that the batwing configuration retained significantly fewer individuals per ha of footrope contact (by both weight and number) than the conventional configurations (LMM, $p < 0.05$, Table 2, Fig. 4a and b). Standardizing catches to per ha of total-system contact (to incorporate the otter-board span on the bottom) eliminated some of the significant differences among the conventional and batwing configurations, but not all (Fig. 4a and b). In particular, the cambered otter-board configuration retained significantly more school prawns by weight (by between 11 and 33%) than the other designs, and also at a significantly smaller mean size (15.22 ± 0.11 mm CL) than the batwing configuration (15.52 ± 0.11 mm CL) (FDR, $p < 0.05$; Fig. 4a). Although not significant, the cambered otter-board configuration also caught a smaller mean CL of school prawns than the kilfoil (15.27 ± 0.11 mm CL) and flat-rectangular (15.34 ± 0.11 mm CL) (FDR, $p > 0.05$). No significant differences were detected for catches of fish (LMM, $p > 0.05$; Table 2, Fig. 4c−g).

3.2. Experiment 2−two pairs of otter boards with trawls

The flat-rectangular and batwing otter-board configurations were towed at mean ± SE SOGs and STWs of 1.29 ± 0.01 and 1.28 ± 0.01 ms^{-1}. There was no significant difference in the wing-end spread of the 31-mm mesh trawls rigged between otter-board pairs, nor the distance trawled (LMM, $p > 0.05$; Tables 2 and 3), however like for experiment 1, the AOA, total-bottom contact and drag were all significantly different (LMMs, $p < 0.001$; Tables 2 and 3). The differences between otter-board pairs for AOA, total bottom contact and projected surface area followed those for experiment 1 (Tables 2 and 3). For drag, the parsimonious LMM included a significant interaction between gear and SOG and a significant main effect of current ($p < 0.01$). The predicated mean drags for the two configurations are presented at the centred value of SOG (i.e. drag at average SOGs) and for zero current; under which criteria the batwing configuration had ~15% less drag than the flat-rectangular configuration (Table 3). The fuel rate equated to ~5.28 and ~6.21 L h^{-1} while fuel intensity was ~2.00 and ~2.33 L ha^{-1} for the batwing and flat-rectangular otter boards, respectively (Table 3).

In terms of catches per ha trawled of foot-rope contact, no significant differences were detected between otter-board configurations for any of the variables, although the predicted mean weights and numbers of school prawns were 5.07 and 7.67% lower for the batwing configuration (LMM, $p > 0.05$, Table 2 and 4). Further, although there were few data (n =

104), the LRT p-value for yellowfin bream catches was 0.09, with a corresponding 1.4 times mean increase in the numbers retained in the batwing configuration (Table 2 and 4).

3.3. Experiment 3−two otter boards without trawls

Substituting a trawl with wire stays between the paired flat-rectangular and batwing otter boards presented few logistical problems, with both configurations towed at mean ± SE SOGs and STWs of 1.31 ± 0.01 and 1.69 ± 0.06 ms^{-1}. Compared to the flat-rectangular otter-board pair, the batwing pair were spread significantly wider (11% difference in predicted means) and at a lower AOA (20 ± 00 vs 32.59 ± 2.13°; LMM, $p < 0.01$; Tables 2 and 3). The parsimonious LMM for drag comprised a significant interaction between otter-board configuration and SOG, and a main effect of current ($p < 0.01$; Table 3). At average SOG and for zero current, the predicated mean drag of the batwing pair was 116.75 ± 3.77 kg, or 26% less than that for the flat-rectangular otter board (158.65 ± 3.79 kg; Table 3).

4. Discussion

Compared to the conventional otter boards, the batwing consistently demonstrated a superior engineering performance, ultimately manifesting as maintenance of sufficient trawl SR with the least drag and therefore the lowest fuel intensity and rate (up to 2.26 L h^{-1} or 0.96 L ha^{-1} lower, for double rig in the tested fishery). This result can be attributed to the two key aspects of the batwing's design: (i) a baseplate aligned with the tow direction, which eliminated the shearing force on the bottom; and (ii) the hinged, hydrodynamic wing with a low AOA (20°), which reduced hydrodynamic drag (Sterling and Eayrs, 2010).

The inherent, consistent engineering benefits of the batwing are quite important, given that fuel can represent a large proportion (up to 30%) of a trawler's operating costs (e.g. Thomas et al., 2010). Any reduction in the overall trawl system drag will help to alleviate some of the fuel used during trawling; of which conventional otter boards typically represent anywhere from 30% in single rig configurations (Sterling and Eayrs, 2010) to the 56% estimated here in experiment 3 (by comparing with data from experiment 2). Based on our data for the studied fishery, replacing any of the conventional otter-board pairs with the batwing would reduce fuel while trawling by between 16 and 22%, which would equate to between ~$A 2−3 K per fishing season.

While there are numerous conventional otter-board designs, often incorporating complex foil and camber arrangements, which might similarly reduce hydrodynamic drag and improve efficiency, many fishers still use basic designs like the flat-rectangular (Patterson and Watts, 1985; Sterling et al., 2000). The popularity of the flat-rectangular otter board among local fishers is supported by the results from experiment 1, with it having the least drag (by ~5%) of the conventional designs. Until recently, in many fisheries, the flat-rectangular otter board was among the most common designs operated (e.g. nearly 100% usage in Australian prawn fisheries until the mid-1980s; Sterling and Eayrs, 2010); reflecting a combination of its simple, easily constructed and maintained design, and comparative efficiency to many contemporary otter boards when operated at 30–40° AOA (e.g. Patterson and Watts, 1985; Seafish et al., 1993).

While it is imperative that otter boards are appropriately rigged to maximise hydrodynamic performance (Sterling and Eayrs, 2010), their overall length is also important in terms of habitat impacts. For example, the cambered otter boards tested in experiment 1 had high substrate contact (~62% of their length at the average 38.62° AOA). The batwing offers a real solution to minimising habitat impacts by having its main substrate contact (the sled) aligned in the direction of towing. Specifically, a conventional otter board 1.12 m long (the same as the batwing) operating at a typical AOA of 35–40° will have ~0.64–0.72 m of lateral contact compared to the ~0.1 m wide baseplate (assuming minimal habitat disturbance of the 'flap') for the batwing. Using an otter board with a fixed (or low) AOA would also reduce system contact, but as demonstrated in experiment 1, a combination of AOA and otter-board length needs to be considered, because a long otter board at a shallow AOA could still contact more of the sea bed than a short design at a more acute AOA.

While reducing total system contact via otter-board configurations may help to mitigate habitat impacts, a concomitant effect could be reduced catches of penaeids (Broadhurst et al., 2012). The cambered otter boards currently are the preferred design in the Clarence River fishery—primarily because they are perceived to catch more school prawns (supported by the results here) than other contemporary designs, which may in part result from their substantial ground contact. However, it is also possible that their large projected surface area (in the direction of the tow) is important. Specifically, this design had more projected area (~18–95% or ~0.07–0.24 m^2 after adjusting for AOA) than the other otter-board designs. Even a small increase in projected area may have directed more school prawns towards the trawl mouth. Such effects might also explain why, despite the lower substrate contact, the batwing maintained catches of school prawns in experiment 2. Specifically, the large sail and flap might have deflected some individuals close to the substratum into the trawls.

While the cambered otter boards improved school prawn catches, this was somewhat offset by their lower fuel efficiency than the flat-rectangular design. Such a result supports the concept that before implementing new otter-board designs (or other modifications), an holistic approach is necessary that allows profit margins to be maintained while increasing ecological efficiency. A comprehensive set of experiments (e.g. testing with a variety of trawl designs in different fisheries) is required; otherwise fishers are unlikely to commit to the continued use of new designs over the long term (Jennings and Revill, 2007).

It is also clear that introducing any technical modification requires careful adjustment and refinement across a broad range of conditions as possible prior to use. For example, in experiment 1, the batwing was associated with significantly lower catches of school prawns than the conventional otter-board designs. We attributed this result to the more dynamic net attachment points—movable wire cables instead of fixed points on conventional designs—which may have permitted the trawl wing to operate slightly higher in the water column, allowing sustained lateral opening of the meshes down the sides of the trawl—thus increasing escape opportunities. Using the batwing and flat-rectangular boards with the smaller (32 mm) meshed trawls in experiment 2 negated these issues and resulted in catches not being significant different for the two otter board types. The importance of electronic monitoring equipment (e.g. Notus sensors and fuel meters) was reinforced by observing that changing to the smaller mesh trawl did not affect the relative differences in performance (e.g. wing-end spread, drag and fuel rates) between experiments.

The results from this study suggest that the batwing otter board has good potential for reducing fuel consumption while maintaining the catching performances of the assessed penaeid trawls. Using otter boards with minimal substrate contact (such as the batwing) will also potentially reduce damage to trawled areas (van Marlen et al., 2010). While creating the definitive otter board may ultimately be difficult to achieve, we believe that to make significant improvements to overall trawl efficiency it may be more conducive to focus further research on an otter-board design that has already attained satisfactory engineering performance (e.g. the batwing) and work on improving its catching performance. The pair of batwings tested here would cost ~$A 3 K which is comparable to purchasing a pair of flat-rectangular otter boards and ~$A 2 K less than the cambered otter boards. Batwing maintenance is equivalent to other otter boards, which combined with their superior fuel efficiency, should facilitate quicker investment returns (i.e. within ~one season, depending on which otter-board design they are replacing).

Alternatively, it might be advantageous to investigate the possibility of modifying existing designs—perhaps to incorporate the key mechanisms of designs such as the batwing to improve engineering and/or catching performances. While not specifically tested, based on our results, an otter board with superior engineering performance will also likely have a lower AOA, which has concomitant potential for reducing habitat impacts (Sterling and Eayrs, 2008; van Marlen et al., 2010).

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Table 1. Scientific and common names and numbers of organisms caught during experiments (Exp) 1 and 2. -, not present in catches.

Family	Scientific name	Common name	Total numbers	
			Exp. 1	Exp. 2
Crustaceans				
Palaemonidae	*Macrobrachium novaehollandiae*	Freshwater prawn	3	-
Penaeidae	*Metapenaeus macleayi*	School prawn	182,568	164,424
	Penaeus monodon	Tiger prawn[1]	1	
Teleosts				
Ambassidae	*Ambassis jacksoniensis*	Port Jackson glassfish	3	5
	Ambassis marianus	Ramsey’s perchlet	11	53
Anguillidae	*Anguilla reinhardtii*	Long-finned eel	8	3
Ariidae	*Arius graeffei*	Forktail catfish	728	86
Apogonidae	*Siphamia roseigaster*	Pink-breasted siphonfish	-	3
Carangidae	*Pseudocaranx dentex*	Silver trevally	-	1
Clupeidae	*Herklotsichthys castelnaui*	Southern herring	275	138
	Hyperlophus vittatus	Whitebait	7	4
Engraulidae	*Engraulis australis*	Australian anchovy	-	2
Gerreidae	*Gerres subfasciatus*	Silver biddy	3	27
Megalopidae	*Megalops cyprinoides*	Oxeye herring	-	3
Monodactylidae	*Monodactylus argenteus*	Diamond fish	6	40
Mugilidae	*Liza argentea*	Flat-tail mullet	-	1
Paralichthyidae	*Pseudorhombus arsius*	Largetooth flounder	-	4
Platycephalidae	*Platycephalus fuscus*	Dusky flathead	1	2
Plotosidae	*Euristhmus lepturus*	Longtail catfish	4	3
Pomatomidae	*Pomatomus saltatrix*	Tailor	12	11
Scatophagidae	*Selenotoca multifasciata*	Old maid	5	4
Sciaenidae	*Argyrosomus japonicus*	Mulloway	184	63
Soleidae	*Synclidopus macleayanus*	Narrow banded sole	81	13
Sparidae	*Acanthopagrus australis*	Yellowfin bream	119	750
	Rhabdosargus sarba	Tarwhine	-	1
Tetrarogidae	*Notesthes robusta*	Bullrout	33	76

Table 2. Summaries of likelihood ratio test (LRT) statistics from linear mixed models assessing the importance of the fixed effect of otter-board pairs in experiments (exp) 1 (flat-rectangular, kilfoil, cambered and batwing attached to identical 41-mm mesh trawls), 2 (flat-rectangular and batwing attached to identical 32-mm mesh trawls) and 3 (flat-rectangular and batwing with no trawls) in explaining variability among key technical and, where relevant, biological responses. Numbers and weights were analysed as log-transformed data, after being standardised to per ha trawled calculated using the foot-rope contact (average wing-end spread × distance trawled) and, additionally where these were significant for the school prawns, the total-system contact ((i.e. wing-end spread + span of otter-board contact) × the distance trawled). −, not present in sufficient numbers. NA, not applicable for analyses; †, no LRT available because the batwing otter board maintained a constant 20^{o} angle of attack (AOA). Owing to a significant interaction with SOG, no main effect of otter board was presented for drag in experiments 2 and 3 (see Table 3).

	LRT		
Technical variables	Exp 1	Exp 2	Exp 3
Wing-end (exp 1 and 2) or otter board (exp 3) spread	1.49	0.04	9.27**
Distance trawled	0.87	1.03	1.07
Otter-board AOA	33.46***	†***	†***
Total bottom contact	41.27***	7.81**	NA
Drag	9.64*	NA	NA
Biological variables			
Wt of school prawns ha^{-1} of footrope contact	18.89***	0.76	NA
Wt of school prawns ha^{-1} of total-system contact	9.13*	NA	NA
No. of school prawns ha^{-1} of footrope contact	12.78**	1.13	NA
No. of school prawns ha^{-1} of total-system contact	6.02	NA	NA
CL of school prawns	8.19*	2.54	NA
Wt of total bycatch ha^{-1} of footrope contact	0.72	0.10	NA
No. of total bycatch ha^{-1} of footrope contact	1.00	0.22	NA
No. of yellowfin bream ha^{-1} of footrope contact	–	2.87	NA
No. of forktail catfish ha^{-1} of footrope contact	3.36	0.41	NA
No. of southern herring ha^{-1} of footrope contact	4.47	0.42	NA
No. of mulloway ha^{-1} of footrope contact	0.69	–	NA

*$p < 0.05$

**$p < 0.01$

***$p < 0.001$

Table 3. Summary of predicted mean ±SE wing-end spreads or footrope contact (m), otter-board angles of attack (AOA), otter-board projected area (m^2), total bottom (foot rope + otter-board base-plate linear span) contact (m), drags (kgf) and subsequent estimated fuel rates and intensities for four pairs of otter boards (flat-rectangular, kilfoil, cambered and batwing otter boards) attached to identical 41-mm mesh trawls in experiment 1 and two pairs of otter boards (flat-rectangular and batwing) attached to identical 32-mm mesh trawls in experiment 2, and spread, AOA and drags for the pairs of the flat-rectangular and batwing otter boards tested without trawls in experiment 3. Mean predicted drags were derived with a centred value of speed over the ground and with zero current. The predicted areas (of individual otter boards) were derived from the percentage of overall surface area when correcting for AOA. Dissimilar superscript letters within experiments indicate significant differences detected in false-discovery-rate pairwise comparisons (experiment 1) or linear mixed models (experiments 2 and 3) ($P < 0.05$). −, Not applicable.

	Otter board pairs			
	Flat-rectangular	Kilfoil	Cambered	Batwing
Experiment 1− four otter-board pairs with 41-mm mesh trawls				
Wing-end spread or foot rope contact (m)	5.08 (0.06)^{A}	5.17 (0.06)^{A}	5.13 (0.06)^{A}	5.10 (0.06)^{A}
Otter-board AOA (^{o})	32.83 (0.40)^{C}	30.58 (0.40)^{B}	38.62 (0.40)^{D}	20 (0.00)^{A}
Otter-board projected area (m^2)	0.41	0.29	0.48	0.25
Total bottom contact (m)	6.58 (0.07)^{B}	6.44 (0.07)^{B}	6.47 (0.07)^{B}	5.30 (0.07)^{A}
Drag (kgf)	251.57 (2.45)^{B}	264.94 (3.18)^{C}	264.46 (2.46)^{C}	216.33 (3.18)^{A}
Fuel rate (L h^{-1})	5.82	6.13	6.12	5.00
Fuel intensity (L ha^{-1})	2.57	2.66	2.68	2.20
Experiment 2− two otter-board pairs with 32-mm mesh trawls				
Wing-end spread (m)	5.17 (0.12)^{A}	–	–	5.12 (0.12)^{A}
Otter-board AOA (^{o})	33.71 (0.98)^{B}	–	–	20 (00)^{A}
Otter-board projected area (m^2)	0.42	–	–	0.25
Total bottom contact (m)	6.73 (0.15)^{B}	–	–	5.32 (0.15)^{A}
Drag (kgf)	268.14 (2.08)^{B}	–	–	227.93 (2.01)^{A}
Fuel rate (L h^{-1})	6.21	-	-	5.28
Fuel intensity (L ha^{-1})	2.33	-	-	2.00
Experiment 3− two otter-board pairs without trawls				
Otter-board spread (m)	2.59 (0.10)^{A}	–	–	2.92 (0.10)^{B}
Otter-board AOA (^{o})	32.59 (2.13)^{B}	–	–	20 (00)^{A}
Drag (kgf)	158.65 (3.79)^{B}	–	–	116.74 (3.77)^{A}

Table 4. Differences in predicted mean catch variables per ha trawled of foot-rope contact (average wing-end spread × distance trawled) between identical 32-mm mesh trawls spread with pairs of flat-rectangular and batwing otter boards.

Variables	Batwing	Fla-rectangular
Wt of school prawns ha^{-1} trawled	5.43	5.61
No. of school prawns ha^{-1} trawled	2044.76	2209.02
Wt of total bycatch ha^{-1} trawled	0.46	0.48
No. of total bycatch ha^{-1} trawled	16.00	17.57
No. of yellowfin bream ha^{-1} trawled	9.61	13.37
No. of forktail catfish ha^{-1} trawled	0.86	0.76
No. of southern herring ha^{-1} trawled	1.74	1.43

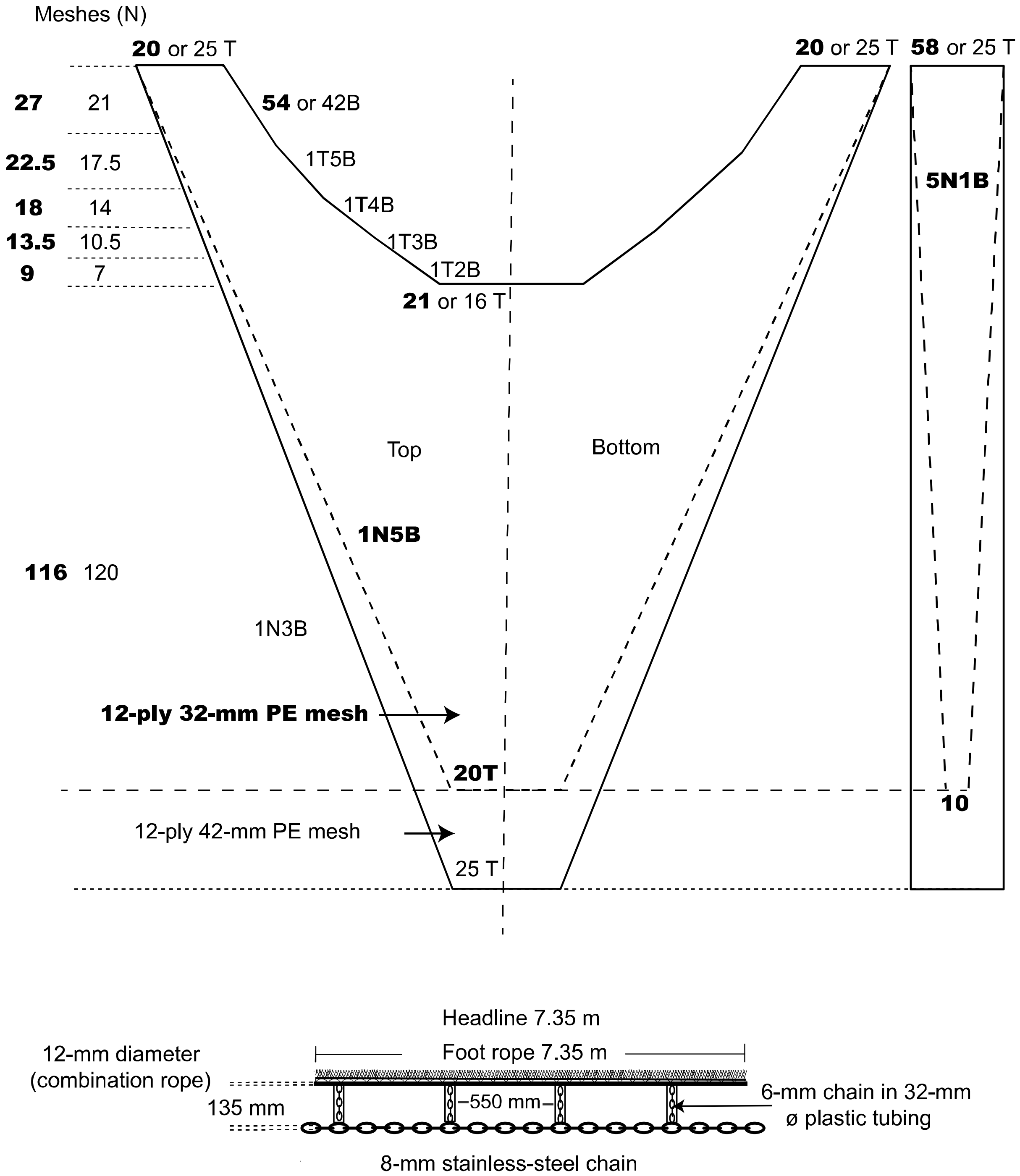
Captions to Figures

Fig. 1. Plans of the 41-and 32-mm trawls used in the study. N, normal; T, transversals; B, Bars; and Ø, diameter (information in bold is specific to the 32-mm trawl).

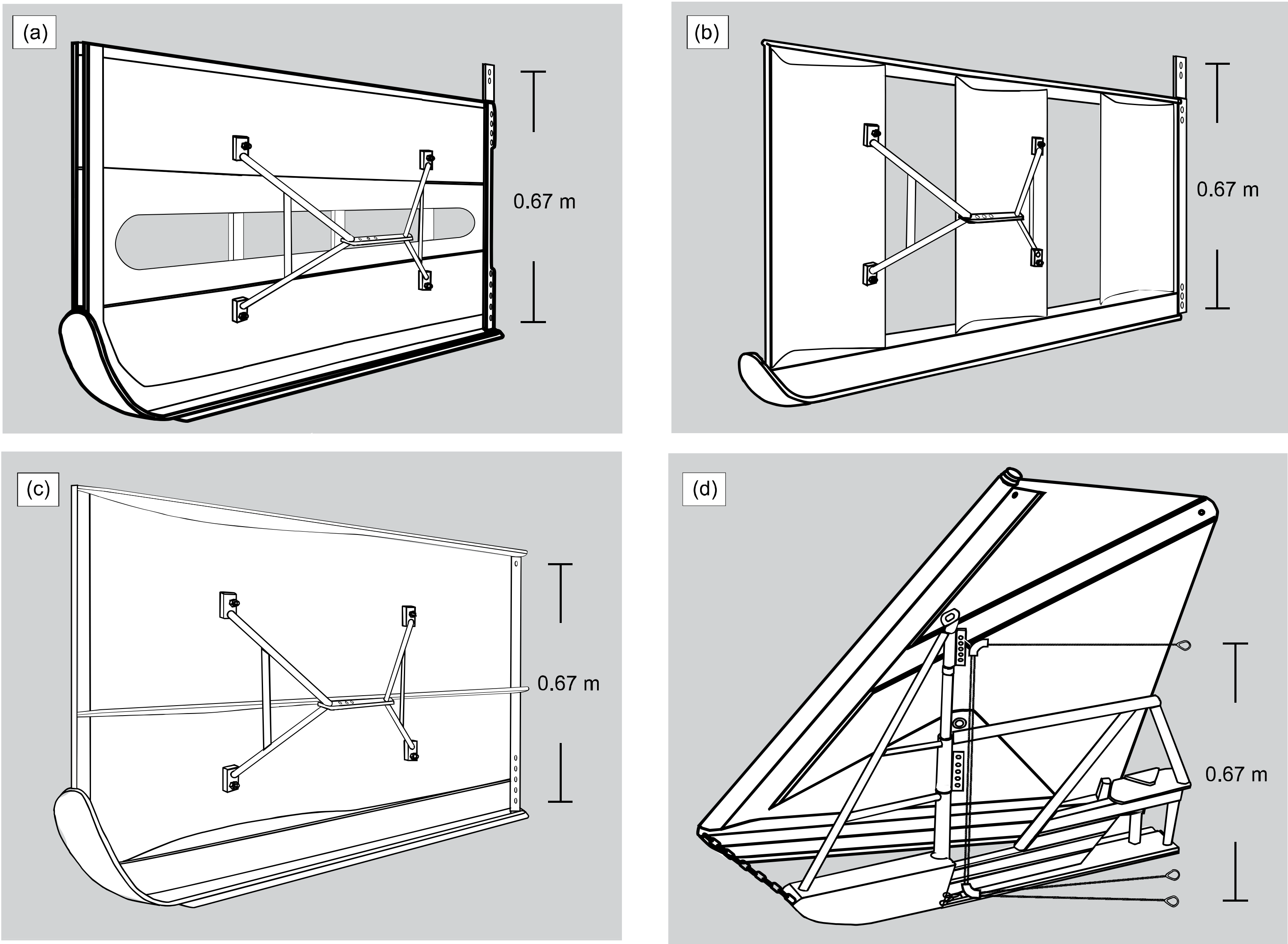
Fig. 2. Three dimensional representation of a) flat rectangular, b) kilfoil, c) cambered and d) batwing otter boards. The 0.67 m represents sweep-line attachment points.

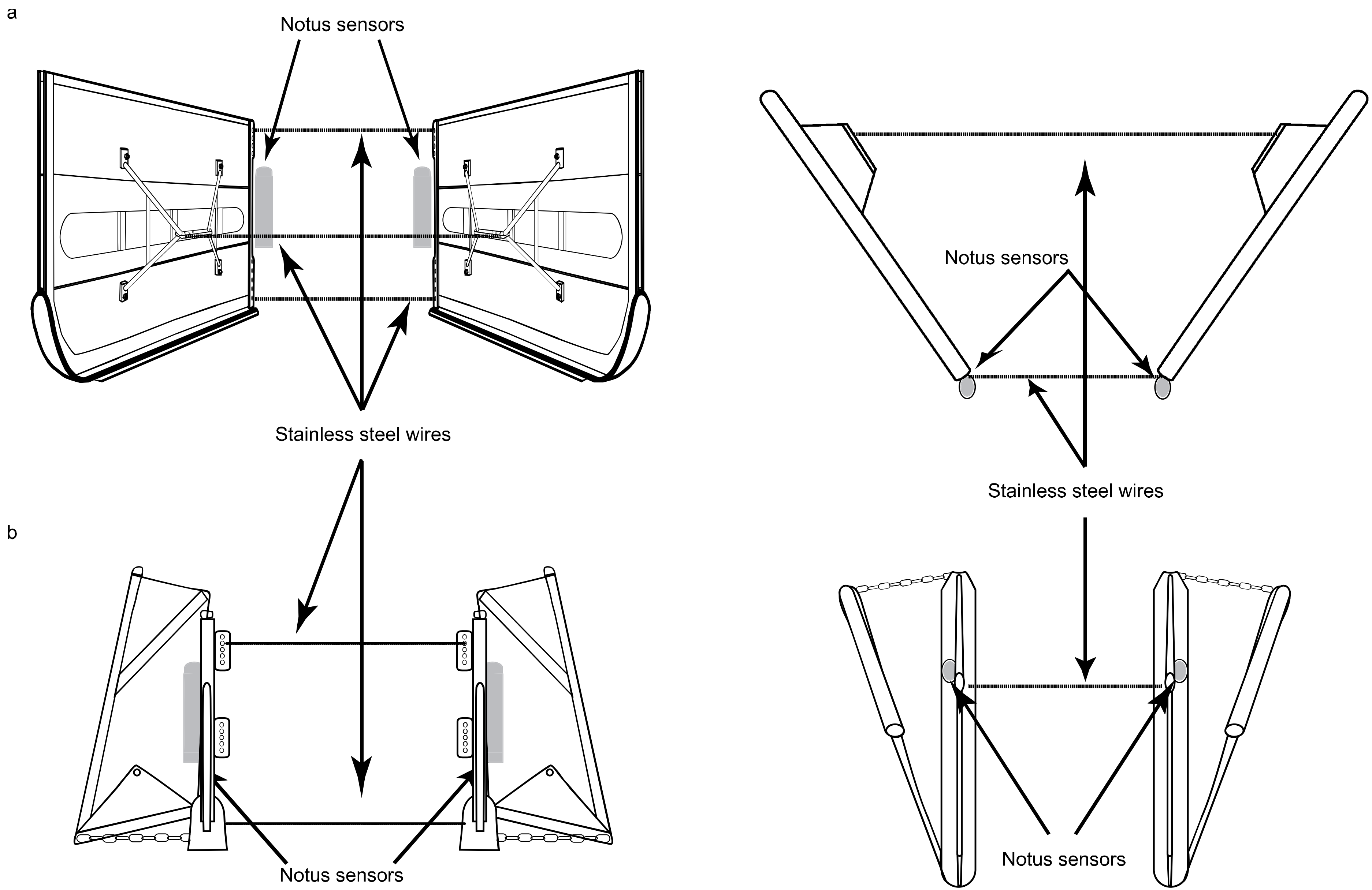
Fig. 3. Front and top views of the (a) flat-rectangular and (b) batwing otter boards rigged without a trawl in experiment 3.

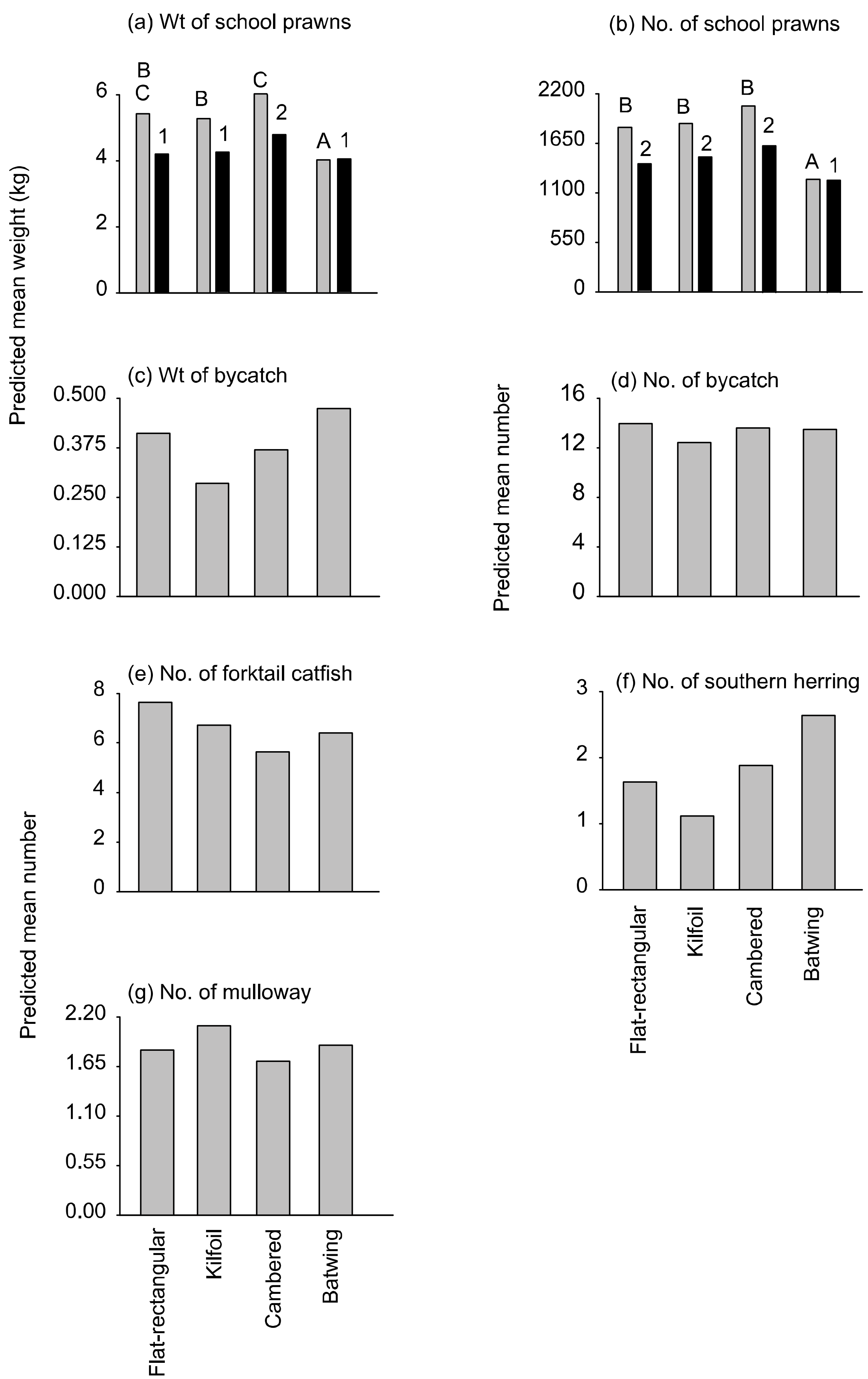
Fig. 4. Differences in predicted mean catches per ha trawled of foot-rope contact (grey histograms) and, where relevant, total-system contact (black histograms) between identical 41-mm mesh trawls spread with pairs of flat-rectangular, kilfoil, cambered and batwing otter boards for the (a) weights and (b) numbers of school prawns (*Metapenaeus macleayi*), (c) weights and (d) numbers of bycatch and numbers of (e) forktail catfish, *Arius graeffei*, (f) southern herring, *Herklotsichthys castelnaui* and (g) mulloway, *Argyrosomus japonicus*. Dissimilar letters and numbers above the histograms indicate significant differences detected in false-discovery-rate pairwise comparisons ($p < 0.05$).


Meshes (N)
20 or 25 T
20 or 25 T
58 or 25 T
27 21
54 or 42B
22.5 17.5
1T5B
5N1B
18 14
1T4B
13.5 10.5
1T3B
9 7
1T2B
21 or 16 T
Top
Bottom
1N5B
116 120
1N3B
12-ply 32-mm PE mesh
20T
10
12-ply 42-mm PE mesh
25 T
Headline 7.35 m
12-mm diameter
(combination rope)
Foot rope 7.35 m
135 mm
550 mm
6-mm chain in 32-mm
ø plastic tubing
8-mm stainless-steel chain

605


(a)
0.67 m
(b)
0.67 m
(c)
0.67 m
(d)
0.67 m


a
Notus sensors
Stainless steel wires
Notus sensors
Stainless steel wires
b
Notus sensors
Notus sensors


(a) Wt of school prawns
(b) No. of school prawns
(c) Wt of bycatch
(d) No. of bycatch
(e) No. of forktail catfish
(f) No. of southern herring
(g) No. of mulloway
Predicted mean weight (kg)
Predicted mean number
Predicted mean number
Flat-rectangular
Kilfoil
Cambered
Batwing

Appendix 5. McHugh, M. J, Broadhurst, M. K., Sterling, D. J., Skilleter, G. A., Millar, R. B. and Kennelly, S. J. (2015) Relative benthic disturbances of conventional and novel otter boards. *ICES Journal of Marine Science* **72**: 2450–2456

Relative benthic disturbances of conventional and novel otter boards

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Abstract

Reducing otter-board angle of attack (AOA) has been proposed as a way to limit the habitat impacts of demersal trawls, but there are few quantitative assessments. This study tested the hypothesis that a novel otter-board design, termed the ‘batwing’ (comprising a 0.1-m wide sled with an offset sail at 20^{o} AOA) would have relatively fewer bottom impacts than a conventional flat-rectangular otter board (35^{o} AOA, with a similar hydrodynamic spreading force). Pairs of each otter board were suspended beneath a purpose-built rig comprising a beam and posterior semi-pelagic collection net and repeatedly deployed across established trawl grounds in an Australian estuary. Compared to the conventional otter-boards, the batwings displaced significantly fewer empty shells (*Anadara trapezia* and *Spisula trigonella*) by 89% and school prawns (*Metapenaeus macleayi*) by up to 78%. These rates were similar to the difference in base-plate bottom contact (87%). Further, the batwing damaged proportionally fewer damaged shells, attributed to their displacement away from the board’s surface area. Other debris (lighter pieces of wood) and benthic fish (bridled gobies, *Arenigobius bifrenatus*) were not as greatly mobilised (i.e. reduced by 50 and 25%, respectively); possibly due to their position on or slightly off the bottom, and a similar influence of hydrodynamic displacement by the hydro-vane surface areas. Although the consequences of reducing otter-board bottom contact largely remain unknown, low AOA designs like the batwing may represent a practical option for fisheries where trawling is perceived to be hazardous to sensitive habitats.

Keywords: Batwing, habitats, hydrodynamic drag, impact, otter boards

Introduction

Demersal trawling occurs throughout the world's oceans and is believed to have originated in the mid-14th century with a design called the 'wondyrchoum'; essentially a precursor to modern beam trawls (Robinson, 1996; Kennelly and Broadhurst, 2002). Technology evolved to 'otter trawling' in the late 19th century, which involves the nets being horizontally spread by the relative flow of water (from forward motion of the gear) acting on hydro vanes (or 'otter boards') (Jones, 1992; Auster and Langton, 1999). Since the early 20th century, otter trawling has become established as the world's most widely-used mobile fishing gear and is considered a principal source of anthropogenic disturbances to benthic habitats (Jones, 1992; Auster and Langton, 1999; Collie *et al.*, 2000; Kaiser *et al.*, 2002).

Many concerns about habitat impacts associated with demersal otter trawls have focused on the otter boards, which leave discernible marks on the substratum, and in some cases lead to unwanted ecosystem impacts (Dayton *et al.*, 1995; Auster and Langton, 1999; Kaiser *et al.*, 2002). Substrate type (e.g. hard or soft) and its mobility will dictate the impact of otter boards and recovery times, whereby soft sediments (e.g. mud and sandy-mud) with a low level of natural disturbance, will be most affected and take longer to recover than harder substrates (e.g. sand) (DeAlteris *et al.*, 1999, 2000; Dernie *et al.*, 2003).

While otter-board impacts are a direct function of their weight and contact pressure (by necessity they have the greatest concentrated mass within demersal trawls), there are two other key factors that ultimately affect the substrate contact area. First is the height-to-length ratio, or aspect ratio of the foil, which determines the otter board's length for a given foil surface area (Patterson and Watts, 1985; Seafish *et al.*, 1993). Second is the operational angle of attack (AOA), which typically is between 30 and 45° (Patterson and Watts, 1985; Seafish *et al.*, 1993). Considering these two factors, an otter board's lateral span of seabed contact can be deduced from simple trigonometry to be the base-plate width, for an AOA of 0°, to a maximum of the base-plate length, for a hypothetical 90°AOA.

Many conventional demersal otter boards are flat and rectangular with a low aspect ratio to match their high AOA (>35°); which although not required to adequately spread the trawls during fishing (i.e. 30° is most effective, while ~20° is the most efficient), ensures their stability during deployment (Sterling and Eayrs, 2010). A novel, high-aspect otter-board design that achieves a consistent low AOA and has good stability is the 'batwing' (Sterling and Eayrs, 2008; McHugh *et al.*, 2015). The batwing foil—comprising a polyurethane (PU) sail set on a stainless-steel boom and mast—acts like an independent kite with a single longitudinal connection to the trawl system via a heavy main sled made from mild and stainless steel. The batwing is configured so that the sled base-plate aligns to the tow direction, while the sail has a consistent AOA (20^{o}) and rides on a PU 'flap' that passes lightly over the seabed on a layer of high pressure water for most of its length. Conceivably, because the batwing mostly contacts the seabed via its base-plate width (assuming the sail has minimal contact) it should evoke proportionally fewer habitat disturbances than conventional, low-aspect and high AOA otter boards.

Identifying component-specific effects on habitats are difficult when using a complete trawl configuration (i.e. otter boards, net, ground gear and associated gear; Gilkinson *et al.*, 1998). One method is via in-situ observations (e.g. video and sonar imaging), although in some fisheries these are limited owing to low visibility and difficulties discerning trawl-mark longevity (existing or new) (Smith *et al.*, 2007). Furthermore, proper experimental procedures require observations (e.g. video and sonar) to be collected before, during and after planned experiments (Schwinghamer *et al.*, 1998); which can be a difficult task in established fisheries (Dayton *et al.*, 1995).

An alternative option involves assessing broad relative benthic disturbances among different otter boards in the same space and time, which can then be used as a proxy for determining the utility or otherwise of modified designs for conserving habitats. We follow this approach here using a purpose-built test rig comprising a posteriorly located collection net (analogous to a covered codend) to investigate the hypothesis of no differences in the relative substrate disturbances of a conventional flat-rectangular and batwing otter boards. The rig was alternately deployed across flat (sandy-mud), previously trawled areas known to contain large areas of empty shell (*Anadara trapezia* and *Spisula trigonella*) and other macro debris, so that their abundances in the collection net and any inflicted damage could be used as relative indices of disturbance.

Materials and methods

The experiment was completed in Lake Wooloweyah (29° 26’S 153° 22’E; ~1–2 m depth), New South Wales, Australia during the Austral autumn, 2014 using a 10-m penaeid trawler (104 kw) configured with two independent hydraulic winches to tow double rig. The trawler had a global positioning system (GPS; Lowrance, HDS5) to record speed over the ground (SOG in m s^{-1}) (every 60 s). The experiment was done at the end of the fishing season and with no other vessels present on the trawled area.

2.1. Otter boards and the testing assembly

Two otter-board pairs were assessed; both with 0.1-m base-plates (Figures 1 and 2). The first otter board pair was termed the ‘flat-rectangular’ and represented a standard design used nationally and internationally, comprising a mild-steel frame with marine-grade plywood inserts (52.53 kg, 1.39 × 0.61 m, solid area of 0.77 m^2; Figure 1a). The second pair was the ‘batwing’; each with a main sled made from mild and stainless steel, and a polyurethane (PU) sail on a stainless-steel boom and mast (60.74 kg, 1.12 × 1.23 m, 0.74 m^2) at a 20^o AOA (Figures 1b and 2a).

Both otter-board pairs were deployed, one pair at a time on a purpose-built test rig comprising a 6-m beam secured at each end to sleds (1.07 × 0.76 × 0.1 m); inside which a ‘collection net’ (a design described by McHugh *et al.*, 2015 and made from 32- and 12-mm polyethylene mesh in the body and codend) was posteriorly attached (Figure 2). The collection net had a 20-cm diameter float attached in the centre of its headline to maximise the vertical opening posterior to the otter boards, but no ground gear. Rather, the lower frame line was attached 0.1 m above and inside the sled base-plates so that it could not contact (nor disturb) the substrate, nor collect any entrained material from the sled (Figure 2).

We validated this lack of substrate contact in earlier work, when the configuration was fished without the attached otter boards (Broadhurst *et al.*, 2015).

The flat-rectangular and batwing otter boards were bolted at their conventional fishing orientations (35 and 0^o base-plate AOA, providing total lateral bottom contacts of 1.60 and 0.20 m, respectively) to independent aluminium frames that could be secured immediately below the beam and 1-m either side of the centre line, so that the base-plates were on the same plane as the sleds, and in front of the collection net (Figure 2). The beam assembly was attached via a 7-m bridle to the towing warps on one side of the vessel, and a conventional otter trawl was operated on the other side (to balance the vessel during towing).

While the tip of the batwings extended slightly higher than the collection net, we did not consider that this would confound the estimates of collected debris. Logic for this statement is based on previous underwater video observations, which revealed that unlike flat rectangular otter boards which disturb the substratum via the baseplate AOA and immediately create quite high sand and debris plumes, the 0^o AOA of the batwing base-plate and only slight contact of the sail foot on the seabed limits the posterior plume in the water column to the lower section (Sterling and Eayrs 2008).

On each fishing day, an otter-board pair was suspended below the beam and deployed for 10 min along independent tracks (Figure 2). The otter-board pairs were alternately deployed among four days and also within two days, providing a total of 36 replicates of each.

2.2. Data collected and statistical analyses

Data collected during each deployment were restricted to the test rig and collection net and included: the total distance (m) trawled (rig on and off the bottom—obtained from the GPS); SOG (m s^{-1}); total catch weight; the numbers and weights of individual fauna; sizes of key species (carapace length−CL for prawns and total length−TL for fish to the nearest 1 mm); and the weights of shells and other debris (mostly water-saturated wood). Estimates of faunal abundance were derived using a 500-g subsample of the total catch, processed in the laboratory. Empty shells were also classified as ‘damaged’ (i.e. broken pieces) or ‘undamaged’ (structurally complete). Owing to difficulties in identifying prawns to the species level, two groups were classified: individuals >5-mm CL (entirely school prawns, *Metapenaeus macleayi*) and those <5-mm CL (some school prawns, but mostly glass shrimp, *Acetes* spp.), termed ‘misc. Dendrobranchiata’.

All data were separately analysed in linear mixed models (LMMs), with some standardised prior to analyses. Catch numbers and weights were analysed as log-transformed data, after being standardised to per 500-m deployment (because of differences in the distance towed—see Results). All other data, including the mean CL of school prawns (>5-mm CL), ratio of damaged and undamaged shells, and deployment distance were analysed in their raw form.

All LMMs included ‘otter-board pair’ as a fixed effect, while ‘days’, ‘deployments’ and, where relevant, their interaction, were included as random terms. All models were fitted using ASReml (Gilmore *et al*., 2006) in the R software package (R Core Development Team, 2014). The null hypothesis of no difference between otter-boards was tested using a Wald *F*-test, which is a modification of the standard Wald test to provide better inference about fixed effects in mixed models. Specifically, the Wald *F*-test is derived by dividing the standard Wald test statistic by the denominator degrees-of-freedom following Kenward and Roger (1997).

Results

A total catch of 87.82 kg was retained in the collection net, comprising school prawns (3.97 kg), misc. Dendrobranchiata (6.29 kg), shells (50.28 kg), wooden debris (12.71 kg), blue blubber jellyfish, *Catostylus* spp. (9.71 kg) and teleosts (4.86 kg). The latter included 23 species, but five comprised 85% of the total (by number): southern herring, *Herklotsichthys castelnaui* (38%); pink-breasted siphonfish, *Siphamia roseigaster* (17%); whitebait, *Hyperlophus vittatus* (15%); Australian anchovy, *Engraulis australis* (11%); and bridled goby, *Arenigobius bifrenatus* (4%).

We attempted to tow the test rig with the batwing and flat-rectangular pairs at similar SOGs (ranging between 1.17−1.53 m s^{-1}) but, while comparable, the mean ± SE deployment distances (833 ± 4.17 and 821 ± 4.17 m) were significantly different (LMM, $p < 0.05$; Table 1). Consequently all numbers and weights are discussed per standardised distance trawled (to 500 m for convenience). Based on the deployment distances, the mean total substrate contacts of the batwing and flat-rectangular pairs were 166.68 ± 0.98 and 1312.86 ± 5.26 m^2, respectively.

Compared to the flat-rectangular otter board's 500-m deployment^{-1}, the net behind the batwing pair had significantly lower: weights of total catch (predicted mean reduced by 80%), empty shells (by 89%) and debris (by 50%); numbers and weights of school prawns (by 78 and 72%); and numbers of bridled gobies (by 25%) (LMM, $p < 0.05$; Figure 2a−e; Table 1). The batwing pair also damaged relatively fewer empty shells (28 ± 0.09 vs 41 ± 0.09% of the total), but directed more (91%) whitebait 500 m deployment^{-1} into the collection net, than the flat-rectangular configuration (LMM, $p < 0.05$; Figure 2f; Table 1).

There was no significant difference in school prawn mean sizes (>5-mm CL) collected behind the batwing (10.31 ± 0.26 mm CL) or flat-rectangular (9.76 ± 0.26 mm CL) otter-board pairs (LMM, $p > 0.05$; Table 1). Although insufficient individuals were caught to enable analyses of mean TL among deployments, the pooled size frequencies of bridled gobies and whitebait were also similar between configurations (Figure 4). There were no other significant differences between treatments (LMM, $p > 0.05$; Table 1).

Discussion

This study represents an innovative approach to describing the reductions in bottom contact and associated habitat disturbances that can be achieved via modifications to otter-board design. The observed relative differences in live catches and non-motile entrained material can be explained by behavioural responses and density-dependant mechanisms related to the substrate contact and AOA of the otter boards.

The results suggest efficiency differences between the flat-rectangular and batwing otter boards, but it should be noted that there was an experimental-design artifact which could potentially confound the interpretation of some variables. Specifically, the otter boards were inside the collection-net wings and closer to the opening than typical trawl configurations. Further, the necessary width of the collection net (i.e. 4.8 m in total) would have meant some organisms were caught, irrespective of the otter boards. Nevertheless, the significant increase in numbers of whitebait, but fewer bridled gobies in the net behind the batwing may reflect its greater aspect ratio and lesser bottom contact. Specifically, whitebait is a schooling species that might have more easily avoided the net behind the flat otter boards owing to their large projected area (a function of the 35^{o} AOA) and the associated visual stimulus (e.g. greater sand clouds). In contrast, bridled gobies are benthic and therefore more likely to be affected by the reduced bottom contact of the batwing.

The observed differences in school prawn catches support the latter hypothesis, with relatively fewer in the net behind the batwing pair and at a rate (72−78%) almost proportional to the concomitant reduction in otter-board base-plate contact (87%). The same effects were hypothesised to account for significant differences in school prawn catches between beam (i.e. just sleds) and otter trawls previously tested in the same lake (Broadhurst *et al*., 2012), but did not extend to the batwing when conventionally rigged to otter trawls (McHugh *et al*., 2015). Such differences possibly reflect spatial or temporal variability in school-prawn behaviour in terms of their level of activity and catchability (emergence from the substrate). Dendrobranchiata catches were not similarly affected here, but the glass shrimp were probably dispersed higher in the water column. Further, the small size of glass shrimp would have precluded any sustained swimming ability (e.g. Daniel and Meyhofer, 1989) or active escape response.

The relationship between entrained material and base-plate contact was further supported by the non-motile catches, and especially shells. For example, the batwing pair displaced 89% fewer shells into the collection net than the flat rectangular; almost exactly the same as the reduction in base-plate contact (87%). Further, the batwing damaged proportionally fewer shells, which may reflect the mechanism of displacement. The flat-rectangular otter board would have displaced shells along the length of the base-plate with its intense ploughing action, and guided some of the shells into the collection net by contact with the timber-and-steel hydro vane. In contrast, the batwing would have displaced fewer shells with the ramped, leading edge of the base-plate, with only some then contacting the PU sail.

While physical contact is an important factor affecting the displacement of dense material/organisms, otter boards also mobilise sediment via their hydrodynamic action (Main and Sangster, 1981; O’Neill and Summerbell, 2011). For example, the amount of material entrained by an otter board can be related to its hydrodynamic drag (O’Neill and Summerbell, 2011), because this is a measure of the rate at which energy is imparted by the otter board to the otherwise stationary water. This effect—an otter-board’s AOA and resulting hydrodynamic drag—is evident from observations by Sterling and Eayrs (2008), where the water flow around a batwing’s low AOA sail did not separate, and entrained less material (predominantly near its base) than a conventionally rigged flat-rectangular otter board (from which plumes filled the immediately posterior water column).

The relative difference in lighter displaced debris (mostly wood) between designs (e.g. 50%) may reflect the difference in drag of the otter boards and the energy contained in the water turbulence surrounding them while they produce a spreading force. Specifically, it is possible that while the hydrodynamic effects of both boards were not sufficient to displace shells from the sediment, it was nevertheless the key force behind the disturbance/mobilisation of less dense material (like wood) into the collection net, and the extent reflects the relative hydrodynamic drag of the boards.

The results present a useful comparison of habitat disturbance between two contrasting otter-board designs; however, it is important to consider that the consequences in terms of actual ecological impacts remain unknown. Further, the test rig precluded replicating some aspects of conventional operations, including variations in otter-board contact weight and orientation with respect to pitch (tilt) or roll (heel). Notwithstanding the limitations, we believe the method replicated commercially representative otter-board/seabed interactions and provided accurate relative indications of the characteristics of the two designs.

Considering the above, low AOA and high-aspect otter boards like the batwing clearly have the potential to displace less benthic material, and for bivalves, at least, with considerably less physical damage. Further research is required to examine the ecological implications of such reductions in various trawling environments, but the principles developed here might offer practical solutions where trawling in sensitive areas is considered problematic. A concomitant benefit of the batwing design is reduced drag, which has the potential to make trawling more energy efficient (e.g. Broadhurst *et al*., 2015; McHugh *et al*., 2015).

Acknowledgements

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Table 1 Summaries of Wald *F*-values from linear mixed models assessing the importance of the fixed effect of otter-board pair (batwing vs flat rectangular) in explaining variability among catches in the collection net. Numbers and weights are presented in their raw form and prior to analyses were standardised to per 500-m trawled, and then log-transformed. CL, carapace length. –, not relevant.

Variables	Wt (kg)	No.	Wald *F*
Deployment distance	–	–	4.76*
Wt of total catch 500 m^{-1}	53.51	–	26.83***
Wt of school prawns, *Metapenaeus macleayi* 500 m^{-1}	2.42	–	21.56**
No. of school prawns 500 m^{-1}	–	4,794	13.32*
Wt of misc. Dendrobranchiata 500 m^{-1}	3.79	–	2.94
No. of misc. Dendrobranchiata 500 m^{-1}	–	13,219	0.57
Mean CL of school prawns > 5-mm	–	–	2.58
Wt of empty shell 500 m^{-1}	30.93	–	27.61***
Proportion of empty shell damaged	–	–	9.01*
Wt of debris 500 m^{-1}	7.74	–	6.30*
Wt of total teleost bycatch 500 m^{-1}	2.95	–	0.47
No. of whitebait, *Hyperlophus vittatus* 500 m^{-1}	–	185	6.94*
No. of bridled goby, *Arenigobius bifrenatus* 500 m^{-1}	–	55	5.89*
No. of southern herring, *Herklotsichthys castelnaui* 500 m^{-1}	–	473	0.61
No. of pink-breasted siphonfish, *Siphamia roseigaster* 500 m^{-1}	–	211	0.05
No. of Australian anchovy, *Engraulis australis* 500 m^{-1}	–	140	0.05

*$p < 0.05$
**$p < 0.01$
***$p < 0.001$

Captions to figures

Figure 1. Three-dimensional representation of the (a) flat-rectangular (1.39 × 0.61 m; 52.53 kg) and (b) batwing otter boards (1.11 × 1.23 m; 60.74 kg) tested in the study.

Figure 2. Top view of the test-rig frame, collection net and (a) batwing and (b) flat-rectangular otter-board pairs. The highlighted section (c) shows the footrope attachment point (0.1 m from the substrate) on the leading edge of the beam-trawl sled. The recorded lengths (of the fixed and solid structures in a and b) are proportional, but owing to variable dynamics, the net shape and length were estimated.

Figure 3. Significant differences in predicted mean catches in the collection net per 500 m deployment between the flat-rectangular and batwing otter-boards pairs for the weights of (a) total catch, (b) school prawns, *Metapenaeus macleayi*, (c) empty shells (*Anadara trapezia* and *Spisula trigonella*, with the proportion damaged, ± SE), and (d) debris and the numbers of (e) bridled gobies, *Arenigobius bifrenatus*, and (f) whitebait, *Hyperlophus vittatus*.

Figure 4. Size-frequency plots of (a) bridled gobies, *Arenigobius bifrenatus*, and (b) whitebait, *Hyperlophus vittatus* in the collection net per absolute deployment for the flat-rectangular (dashed lines) and batwing (solid lines) otter-board pairs.

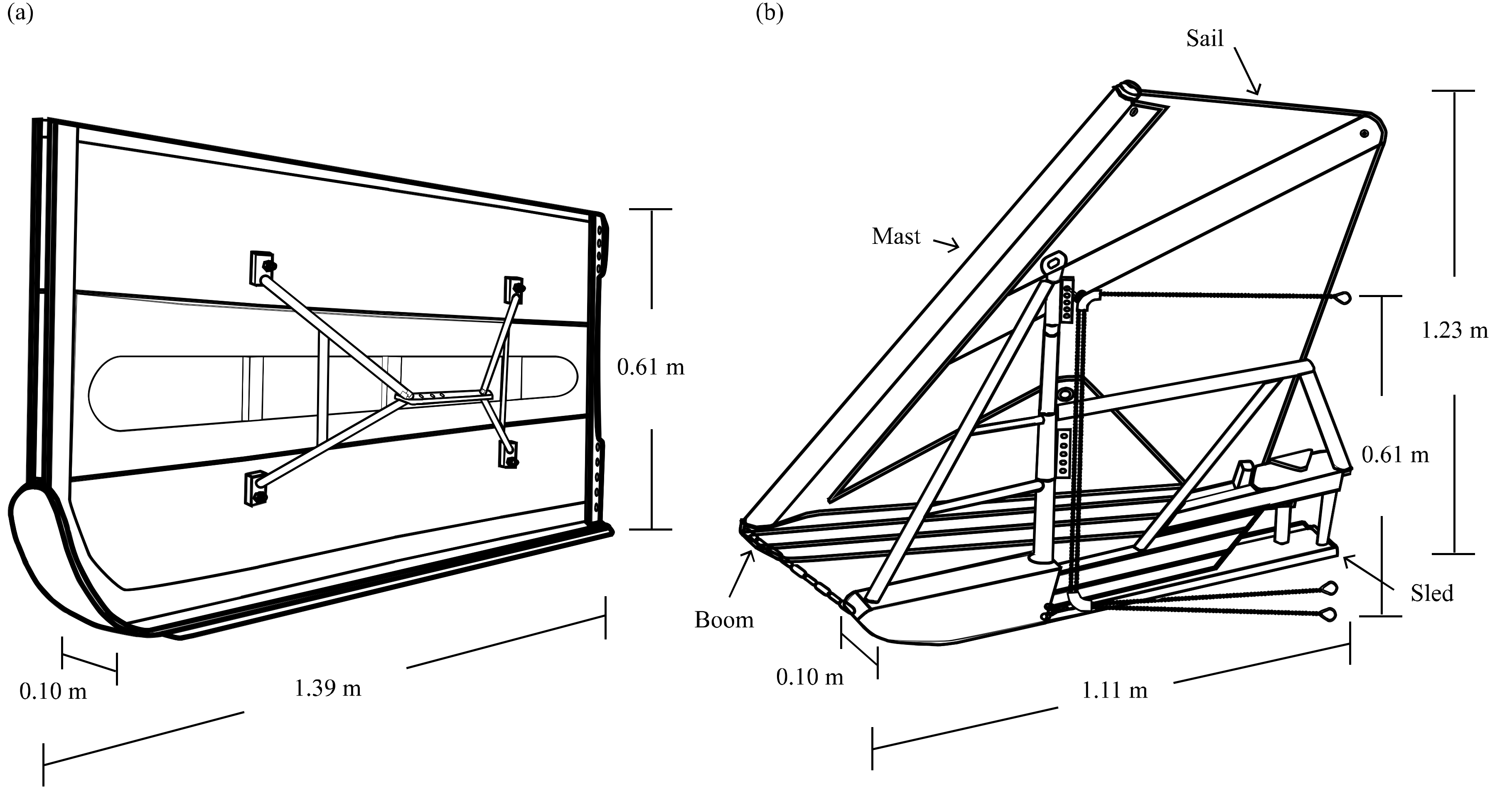

Figure 1

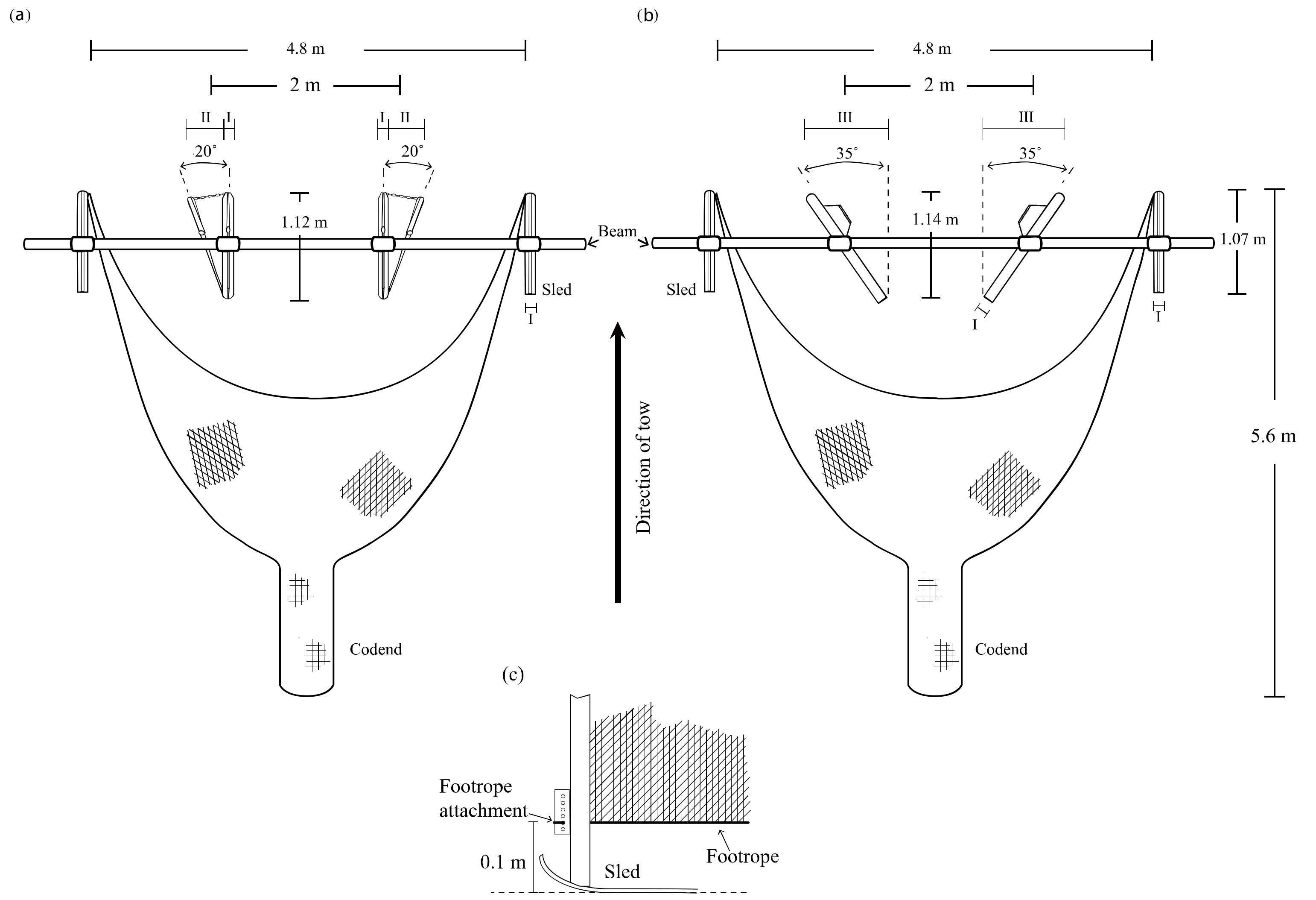
(a)
(b)
4.8 m
2 m
II
I
III
20˚
35˚
1.12 m
1.14 m
1.07 m
Beam
Sled
Direction of tow
5.6 m
Codend
(c)
Footrope attachment
0.1 m
Footrope

Figure 2

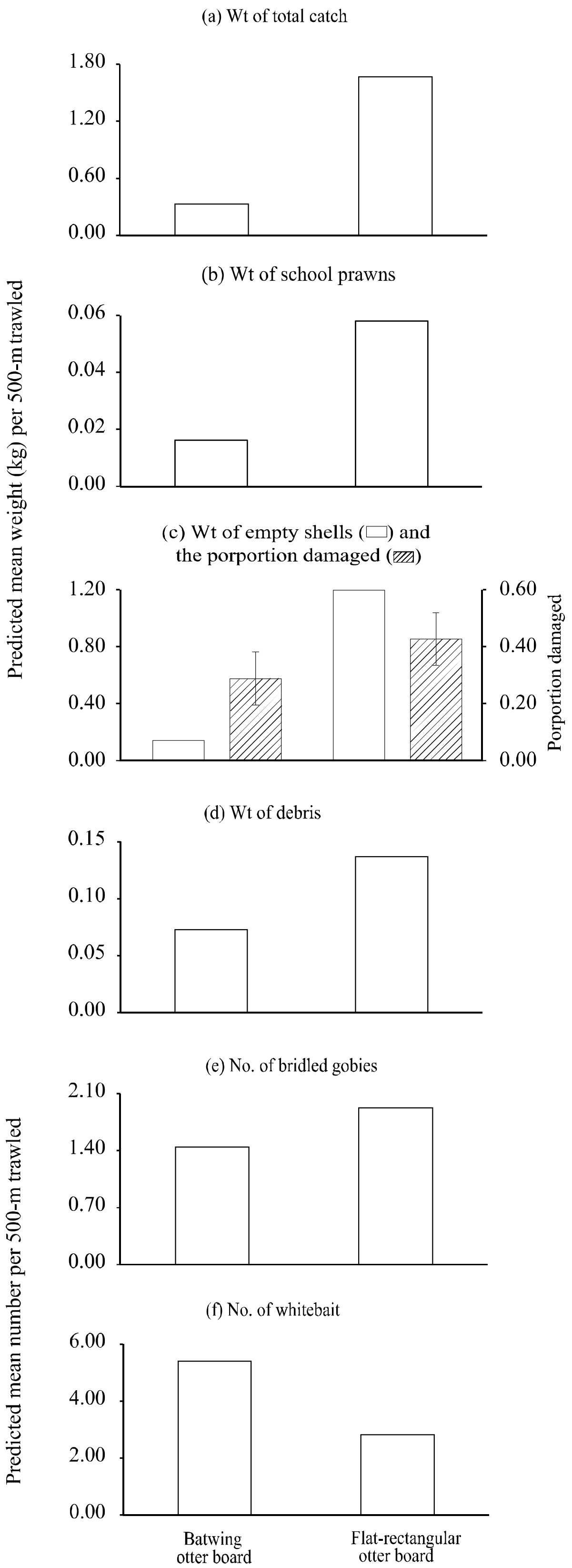
(a) Wt of total catch
1.80
1.20
0.60
0.00
(b) Wt of school prawns
0.06
0.04
0.02
0.00
Predicted mean weight (kg) per 500-m trawled
(c) Wt of empty shells ( ) and
the porportion damaged ( )
1.20
0.80
0.40
0.00
0.60
0.40
0.20
0.00
Porportion damaged
(d) Wt of debris
0.15
0.10
0.05
0.00
(e) No. of bridled gobies
2.10
1.40
0.70
0.00
(f) No. of whitebait
6.00
4.00
2.00
0.00
Predicted mean number per 500-m trawled
Batwing otter board
Flat-rectangular otter board

Figure 3

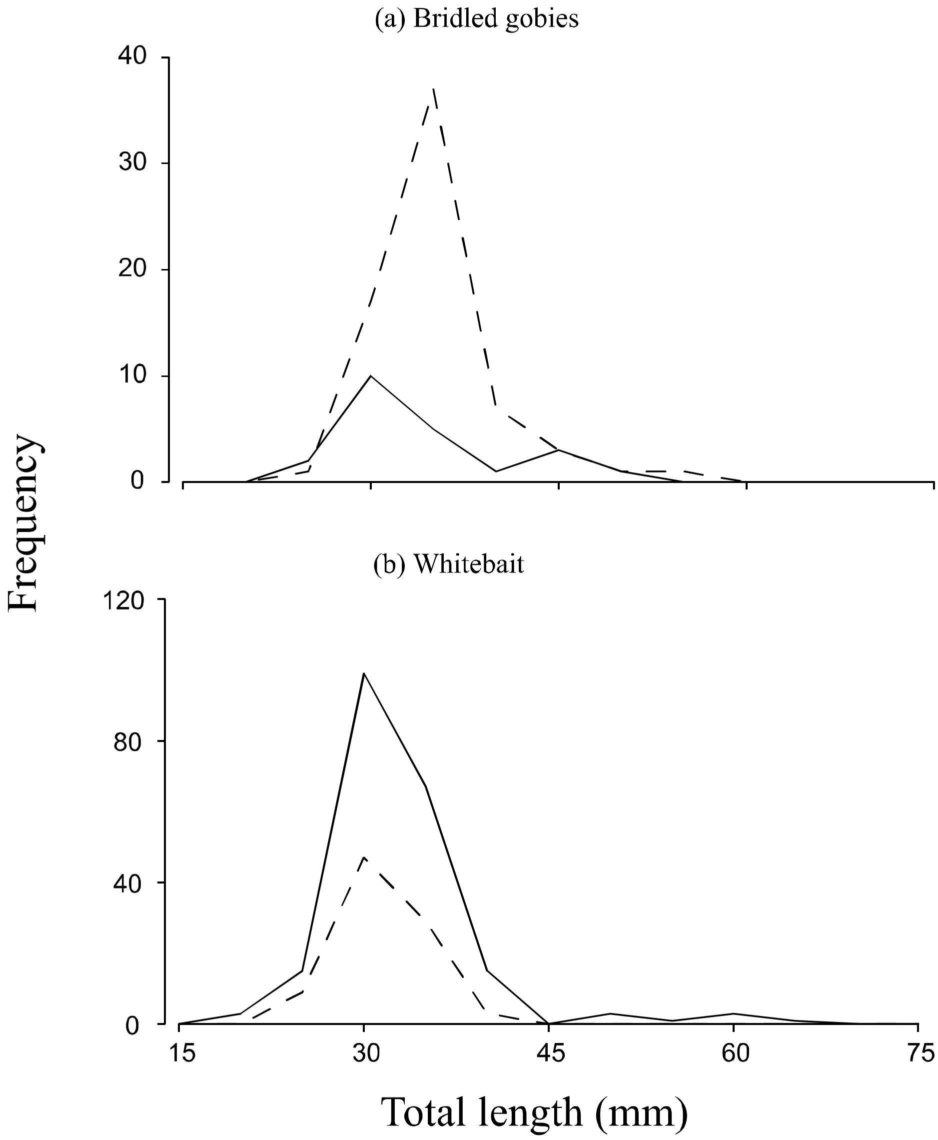
(a) Bridled gobies
40
30
20
10
0
(b) Whitebait
120
80
40
0
15
30
45
60
75
Frequency
Total length (mm)

Figure 4